# An Assessment of the State of Knowledge of East Coast Offshore Wave Climatology

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Marine Environmental Data Service

W.F. Baird

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## CAUTIONARY NOTE

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## ABSTRACT

This report assesses the availability and adequacy of the wind generated wave data required by the oil and gas industry, the design organizations, the classification societies, the regulatory agencies and the research organizations for the development of safe structures to be used in the activities of exploratory and delineation drilling in waters off the East Coast of Canada.

It is found that the minimum requirements of the design, owner/operator, classification and regulatory organizations for wave data are well defined in the available literature and that if these data are available safe and efficient design of structures and associated operations are expected.

It is concluded that the required data are not available throughout the study area. Reliable estimates of the required extreme wave conditions are only available for the Hibernia area and even with these data there are some concerns. Throughout the remainder of the study area data suitable for the estimation of extreme events do not exist. Wave climate statistics suitable for the analysis of operations may exist for the southerly part of the study area, although limitations of these data are also identified. An important requirement identified, is the need for simultaneous observations or predictions of waves, currents and winds. It is not clear that this requirement has been adequately addressed over the study area. The availability of current and wind data is the subject of other reports and has not been examined here.

The future sources of wave data and information on extremes and wave climate are examined and conclusions are drawn. It is concluded that in the near future these data will continue to be developed using traditional techniques. However, improved advanced instrumentation and improved hindcast models better suited to the requirements of the various parts of the study area must be developed and implemented.

Satellite and other remotely sensed data will begin to become available within the next decade in useful quantities and will immediately begin to be useful for operations through improved forecasting. However these additional data will not improve the knowledge of wave climate and extremes for a number of years until a significantly increased database has been accumulated.

The present practice of developing knowledge of wave climate and extreme conditions in the study area is examined. It is noted that this knowledge is now acquired by an accumulation of information from many independent studies which are generally of insufficient scope and not fully co-ordinated with other programs. These studies tend to raise more questions than they answer and often disagree with each other. It is concluded that there is a need to develop joint programs between all interested parties to organize, priorize and carry out the studies to acquire the necessary wave information in the study area.

# Table of Contents

# 1.0 Introduction

## 1.1 Background

The study reported in this document has been carried out on behalf of the Royal Commission on Ocean Ranger Marine Disaster by the Marine Environmental Data Service (MEDS) of the Department of Fisheries and Oceans. The study relates to the second term of reference of the Commission, which was to

*Inquire into, report upon and make recommendations with respect to:*

*a) both the marine and drilling aspects of practices and procedures in respect of offshore drilling operations on the Continental Shelf off Newfoundland and Labrador and without restricting the generality of the foregoing, the matters referred to in paragraphs 1. (a) to 1. (e) *as they relate to other drilling units conducting marine and drilling operations on the Continental Shelf off Newfoundland and Labrador; and*

*b) to the extent necessary and relevant, such practices and procedures in other Eastern Canada offshore drilling operations.*

To address this second term of Reference, the Commission undertook a study program the goal of which was:

*"TO IDENTIFY PRACTICAL MEANS OF IMPROVING THE SAFETY OF EASTERN CANADA OFFSHORE DRILLING OPERATIONS."*

*The study area is Eastern Canadian Offshore (see Figure 1.1) extending from the shoreline to the limits of jurisdictional claims. The area extends from the Canada-US boundary north to the limit of areas which will be serviced from East Coast ports and use marine drilling systems (approximately 75 N).*

*The subject of study is offshore exploration and delineation drilling operations, including service and supply (marine and air) activities.*

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Paragraph 1. (a) is in the first term of reference and refers specifically to the "design construction and stability of the OCEAN RANGER and its suitability to the conduct marine and drilling operations on the Continental Shelf off Newfoundland and Labrador.

Paragraphs 1. (b) to 1. (e) are unrelated to a study of wave climatology.

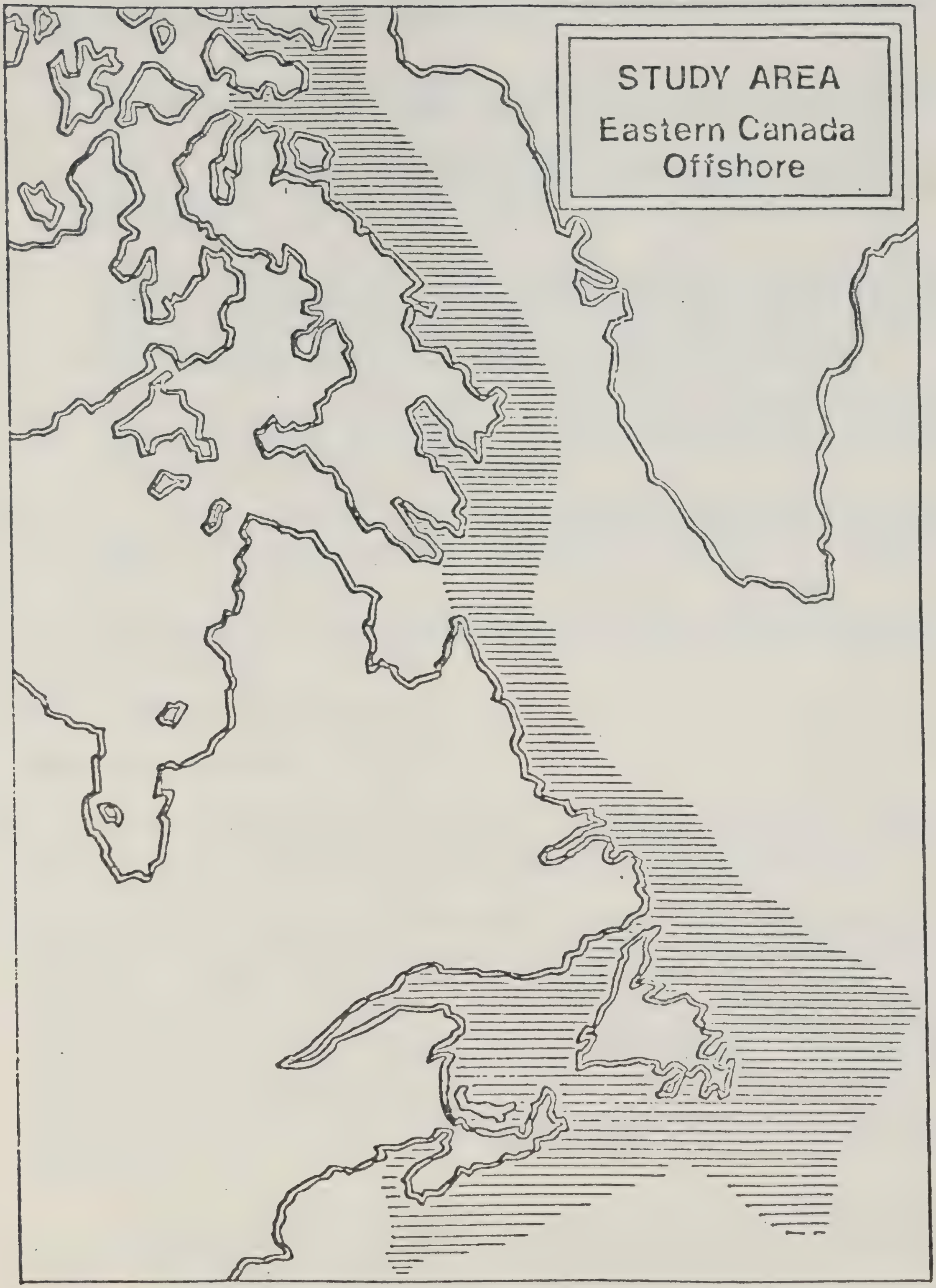



Figure 1.1 Study Areas

## 1.2 Objectives

The present study is one of many, each addressing a particular subject areas of importance to the activities of exploratory and delineation drilling on the East Coast of Canada.

The purpose here was to produce a state of the art assessment of wave climate knowledge for the study area. The following goals were established.

a) Produce a description of the wave data and information available for each geographic area for design, regulation and planning of operational strategies.

b) For each geographical and subject area, synthesize and compare the various relevant datasets and derived parameters, and discuss the adequacy or inadequacy of the results in terms of the state of the art in wave climatology and the requirements for design and operations.

c) Describe the various techniques used to extrapolate to long return period events, and discuss the adequacy of the database and the scientific knowledge to the task of extrapolating.

d) Compare the information and scientific and technical knowledge available to that required for design and operations, and discuss the implications of shortcomings.

e) Draw conclusions where possible on the availability of data, information and knowledge.

f) Identify future study needs.

## 1.3 Overview of the Report

To present a volume of diverse technical material in a fashion to ease its digestion by the reader is never easy. We have attempted a certain organization here and it is hoped that it is at least logical to the reader.

Section 2 discusses the requirements for wave data. It begins with a brief overview and discussion of wind generated waves which is the subject of the study. It goes on to discuss who needs wave data and why. Not surprisingly it turns out that high on the list of people requiring wave data are the design houses, classification societies and regulatory agencies. It therefore became necessary to devote some discussion to design, certification and regulatory procedures and to reproduce some of the rules, guidelines and regulations here. The discussion is given in sections 2.3 and 2.4 primarily. Appendix A contains the rules, guidelines and regulations pertinent to wave climatology.

Section 3 contains the discussion of the available data for the study area and its unavailability and assessment. Section 3 also contains an overview of extreme value analysis procedures and the conclusions of the study.

Section 4 is a brief discussion relating the Canadian situation to the North Sea experience to identify major differences in the approach to the development of wave climate knowledge.

Section 5 reviews several of special study areas such as wave in shallow water, non-conventional wave events and future sources of wave data.

The conclusions were placed in section 3 since the major conclusions related to sections 2 and 3.

## 1.4 Acknowledgements

MEDS is not expert in the engineering applications of waves in the design and operation of offshore structures. The firm of W.F. Baird and Associates was therefore engaged on a major subcontract to assist with those aspects of the study. MEDS gratefully acknowledges their advice and counsel and assistance with the preparation of the report.

In the process on carrying out the work reported here there was a substantial data analysis task. More than 2 million wave spectra were processed and a few thousand tables and maps were generated to provide the data to plot the diagrams and maps in section 3. Several months of dedicated work by Tracey Dougherty and Tom MacLeod of MEDS are acknowledged with thanks.

The typing of the manuscript and equations at the last minute and under the pressure of a passed deadline by Ruth McGarry, Marg Johnstone and Dolores Swift of MEDS is also acknowledged with thanks.

A number of organizations were contacted during the course of this study and they provided a significant contribution through meetings and correspondence. These organizations are noted in section 2.4 and their input is gratefully acknowledged.

Finally the financial support to the project by the Royal Commission and the Office of Energy Research and Development is noted with appreciation.

## 1.5 Other Publications

As stated in section 1.4 above several thousand tables and diagrams of wave characteristics for the various datasets were produced in carrying out the study. It is the intention of MEDS to publish this information in a data report which should be available in the early summer of 1984.

# 2.0 Requirements for Wave Data

## 2.1. An Introduction to Wind Generated Waves

### 2.1.1 General Discussion

A wind generated wave field propagating over the oceans is an extremely complex phenomenon which is not well understood and can only be described by numerical methods that involve many simplistic assumptions.

The intent of this brief overview is to provide an introduction to the problem of adequately describing waves for engineering purposes. This is follwed by a brief introduction to methods of analyzing wave records and a discussion of conventional wave statistics. A glossary of the wave terminology used in this report is included in Appendix B.

Waves are formed by a complex process of wind turbulence acting on the water surface, and their growth is governed by a transfer of energy from the wind to the water. The height of the waves may be limited by the wind velocity, the time that the wind blows, or the distance (fetch) over which the wind blows. The generation process produces an irregular distribution of wave heights and periods. Since the wind speed and direction will also be changing with time the resulting sea-state has a very irregular appearance that cannot be simply described. Waves that move out of the generating area tend to form into longer period and long crested waves of almost constant height, and are known as swell.

A wave to an observer is only the shape of the ocean surface that results from the complex, but generally circular, motion of the water particles below the suface. There is almost no mass movement of water associated with the propagation of waves except when a wave breaks. A piece of wood, floating on the surface follows a circular path, for example. The diameter of the circle is equal to the wave height and the time required to complete the circle is the wave period.

Careful observation of the surface of the ocean in deepwater during a storm will lead to the following conclusions:

- An individual wave is not permanent. It slowly increases in height and then decreases as the wave moves forward. The height of such a wave does not remain constant with time and the wave is said to be dispersive.

- Wind generated waves do not move in the same direction, although the direction of movement of locally generated wind waves will usually be limited to a sector in the order of 90 degrees. As waves move out of the influence of a storm they tend to increase their period and become long crested. These waves are known as swell.

- Waves are generally either short crested or long crested. Short crested waves are associated with a wave field containing waves travelling in a range of directions and long crested waves are associated with swell.

- The slope, or steepness, of the leading side of the wave may be steeper than that of the rear side of the wave.

- The crest of the wave may be unstable or the front slope too steep which produces a cap of white foam or a mass of water moving down the front slope of the wave at a speed faster than the velocity of the wave, a condition known as breaking.

- There is considerable variation in the height and period (or wave length) of the waves in the sea-state. In very severe sea-states wave heights may reach 40 metres, wave periods reach 18 seconds, and wave lengths 500 metres or more. Swell waves may have even longer periods or wave lengths, but the wave height will not be as large.

When considering the visual appearance of waves in a severe sea-state it is important to note that for many engineering procedures it is not the geometry of the sea surface that is important. It is the movement (i.e. displacement, velocity, and acceleration) of the water mass below the surface that produces loads on a structure and this movement must be accurately described to calculate the forces on the structure.

Many mathematical theories or formulations exist to describe the surface profile, and the displacement velocity, acceleration and pressure field below the surface. The simplest theories are valid for small amplitude, long crested waves of constant height moving in a stationary water mass.

### 2.1.2 Methods of Analysis

The most common form of wave record is obtained by measuring the water surface elevation as it passes a fixed point. In fact the point is seldom fixed because the measuring device consists of a tethered buoy on a slack mooring. Therefore, the record consists of a trace of vertical travel of the buoy as it rises over the wave crests and falls to the trough while moving back and forth a certain amount with the waves.

There are two basic methods of analyzing a wave record. The first consists of measuring individual waves from the record, and is referred to as a zero crossing analysis. The second involves breaking down the irregular trace into a series of sine waves of different amplitudes and periods which when added together reproduces the original wave record. This is referred to as spectral analysis. This latter method involves a complex numerical procedure generally known as variance spectral analysis.

The definitions of the parameters derived from the different methods of analysis are summarized in a publication produced by the Permanent International Association of Navigation Congresses (PIANC), PIANC 1973. This glossary is reproduced in Appendix B. The principal parameters referred to in this report are as follows:

$H_{z,max}$ — The maximum zero up-crossing wave height observed in a specified period of time.

$H_{1/3}$ (or $H_s$) — The significant wave height. The average of the highest one third of the zero up-crossing wave heights for a stated period of time.

$T_z$ — The zero-crossing wave period is an average period obtained by dividing the record duration by the number of times the water surface crosses the mean water level in one direction.

$H_{mo}$ — The characteristic wave height = 4 x σ ( σ is the square root of the variance). This parameter is obtained from spectral analysis and is approximately equal to the significant wave height in certain conditions.

$T_p$ — The peak period. The period at which the maximum variance spectral density occurs.

$H_v$ — Wave height from visual observation. The average height of the larger well formed waves.

$T_v$ — Wave period from visual observation. The average period of the larger well formed waves.

### 2.1.3 Short Term Wave Statistics

During the peak of a storm it is normally assumed that for a relatively short, but defined period of time, the average wave conditions do not change. This condition is referred to as stationarity and it may be assumed to last from one hour to six or more hours. This section provides a brief summary of wave statistics when wave conditions are stationary.

It is common practice to assume that the distribution of wave heights, obtained from a measured wave record follows a Rayleigh distribution of the form:

$$P(H \geq H') = exp\left[\frac{-2H'^2}{H_s^2}\right]$$

which gives the probability that a wave height, H, equals or exceeds a selected value, H'. $H_s$ is the significant wave height.

This distribution allows relationships between various wave height parameters to be determined, as illustrated in the following table:

| | $H_{mp}$ | $H_{av}$ | $H_s$ | $H_{1/100}$ | $H_{1/100}$ |
|---|---|---|---|---|---|
| $H_{mp}$ | 1.00 | 0.80 | 0.50 | 0.39 | 0.30 |
| $H_{av}$ | 1.25 | 1.00 | 0.63 | 0.49 | 0.38 |
| $H_s$ | 2.00 | 1.60 | 1.00 | 0.78 | 0.60 |
| $H_{1/10}$ | 2.55 | 2.04 | 1.28 | 1.00 | 0.76 |
| $H_{1/100}$ | 3.34 | 2.67 | 1.67 | 1.30 | 1.00 |

$H_{mp}$ = most probable wave height in the record
$H_{av}$ = average height of all waves
$H_s$ = significant wave height
$H_{1/10}$ = average height of the highest one tenth of all wave heights
$H_{1/100}$ = average height of the highest one hundredth of all waves

Table 2.1 Some statistical relationships between wave heights

The ratio of the probable maximum wave height to an average parameter, such as the significant or characteristic wave height for a stationary sea-state, is commonly assumed to depend on the number of waves that pass the point of measurement during a given period of time. The longer the time, the greater the number of waves and the greater chance of recording a large wave. Table 2.2 provides ratios of the maximum wave height to the significant wave height as a function of the number of waves. The associated duration for a wave period of 10 seconds is also noted.

| No. of Waves | Duration 10 sec. Period | Ratio of Most Probable Maximum Wave to Significant Height |
|---|---|---|
| 50 | 8.3 min. | 1.42 |
| 100 | 16.6 min. | 1.53 |
| 500 | 1.4 hours | 1.77 |
| 5000 | 14 hours | 2.07 |
| 10000 | 28 hours | 2.15 |
| 20000 | 56 hours | 2.23 |

Table 2.2 Ratio of the most probable maximum wave to the significant wave height for various durations of a stationary sea-state.

### 2.1.4 Storms

The calculation of short-term statistics of waves is dependent on the major assumption that the event is stationary. However, storms that generate large wave events are non-stationary, often moving through an area at speeds greater than 45 km/hr. It is probable that the mean wave direction will also be changing in response to wind changes with the passage of the storm. Traditional methods of estimating extreme wave conditions do not provide information on the duration of storms. Consequently, the estimation of the most probable maximum wave height associated with a storm with a long return period in the order of 50 or 100 years must represent a conservative estimate based on the study of probable storm profiles that would be associated with the extreme event.

### 2.1.5 Long-Term Wave Statistics

In general, recorded wave or recorded wind (for hindcasting purposes) data are available for only relatively short periods of time. However, for designing structures that operate in an exposed environment, a design wave condition with a specified return period is required. The return period is determined from the expected life of the structure and the accepted risk of the design storm occurring during the life of the structure. In order to provide the required long-term distribution of wave heights, an extreme value analysis is undertaken using one of many available distributions. The more common distributions used to describe the long-term statistics of waves are the Fisher-Tippet type, Weibull and log-normal distributions. These distributions are discussed further in section 3.6.

An extreme value analysis is a technique used to predict the frequency of occurrence of long return period events. An example would be a 100 year

return period wave which can be thought of as the highest wave one would expect to experience every 100 years. Since 100 year time series of virtually all the geophysical variables of interest do not exist, the extreme value analysis is used to extrapolate probabilities from a shorter period of "data". Time series of wave measurements off Canada's east coast vary from one to 10 years in length. To extrapolate a 5 or 10 year data set of measured waves to a 100 year event is considered to yield unreliable results. It is reasonable to assume that one would get a more reliable prediction of the one hundred year wave if it is predicted from 30 to 50 years of data rather than 10.

Reliable meteorological time series of observed winds extend back to 1950 over the southern portions of the study area. It is therefore considered appropriate to use the measured wind fields to estimate wave conditions and produce a time series of wave data of 20 or 30 years duration for the extreme value analyses. This procedure is referred to as "hindcasting" waves from winds.

The relationship between the probability (or risk) of encountering an event with defined return within the design life of the structure is illustrated in Table 2.3. The design procedures referenced in Appendix A frequently refer to the use of the 100 year event (and occasionally the 50 year event) for the calculation of loadings on, or response of, the structure. This table presents the probability of encountering this event for selected design lifes.

**Encounter Probabilities**

| | | Return Period (years) | | | | |
|---|---|---|---|---|---|---|
| | | 20 | 50 | 100 | 200 | 1000 |
| Design | 1 | .05 | .02 | .01 | - | - |
| Life | 5 | .23 | .10 | .05 | .02 | - |
| (years) | 10 | .40 | .18 | .10 | .05 | .01 |
| | 30 | .79 | .45 | .26 | .14 | .03 |
| | 50 | .92 | .64 | .39 | .22 | .05 |

Table 2.3 Probabilities of encounter for events with various return periods as a function of design life.

### 2.1.6 Non-Conventional Wave Events

There are a number of aspects of wind generated waves that can be described as non-conventional, because they cannot be described in the normal, or conventional, statistical manner. These events include wave grouping and "freak" or "rogue" waves.

The physics which control these events is not well understood and their existence, severity or frequency of occurrence has not been adequately documented in the study area. It is therefore very difficult to assess the influence of these events on the design of offshore structures.

Non-conventional events are discussed in greater detail in section 5.2 of this report.

### 2.1.7 Other Forms of Waves

This report deals entirely with wind generated waves. Other wave forms include tides and tsunami waves.

Tides and tidal currents result from the motion of the moon, sun and the planets and are a phenomenon producing very different effects than do wind generated waves because of their much longer period. Tides have two distinct effects on wind generated waves. The first effect is that the water surface is raised or lowered. Raising the water surface will bring the crests of the wind generated waves closer to the deck of a drilling unit resting on legs sitting on the sea floor. Secondly, a tidal current running against a propagating surface wind-wave causes the wave to steepen and increases its impact or drag on the structure.

Tsunamis or earthquake generated waves are generally of little concern to structures in deep water. However, they can have a devastating effect on coastal structures.

## 2.2 Organization Requiring Wave Data

In the following sections, 2.2.1 to 2.2.5, the principal organizations requiring wave data in their involvement with the exploration or recovery of hydrocarbons are briefly discussed. The requirements of these organizations for wave data are discussed in sections 2.3, 2.4 and 2.5.

### 2.2.1 Design Organizations/Fabricators

A designer, frequently working with a fabricator requires a description of the wave climate to assist in the development of concepts for the structure and for the detailed design process. The form of the concept developed may be significantly influenced by the severity of the environment in which it must survive and operate.

In the detailed design process, a very complete description of the wave climate may be required. However, mobile drilling units are generally designed to survive and operate in a wave climate of a selected severity and not for a specfic site. Many units have been designed to have an unlimited classification and operate in any area of the world. Fixed structures are designed for a specific location and for the wave climate at that location.

### 2.2.2 Owners/Operators

The owner ensures that its structures has been designed for the environment in which it is to be used. To achieve this objective, the operator must have a reliable description of extreme wave, current and wind conditions at the site and must be satisfied that the structure was designed to survive these conditions.

The owner is also concerned with the environment from an operational point of view. Clearly the selected structure must be able to operate efficiently in the climate of the area. In order to design support operations and ensure adequate supplies of consumables, the operator must also have a detailed knowledge of expected downtimes due to wave and other environmental conditions.

In the approval and classification processes, it is the responsibility of the owner to provide the required descriptions of the wave climate, including extreme events, of the area in which the structure will operate.

### 2.2.3 Classificaton Societies

The classification society is principally concerned with survival of the structure and it will undertake a detailed review of the design. The requirements of the classification society is therefore concerned with structural integrity and survival in the same manner as the design engineer.

The following description of the classification process is taken from American Bureau of Shipping 1980:

> *"The Classification process consists of a) the development of Rules, guides, standards and other criteria for the design and construction of marine vessels and structures, for materials, equipment and machinery, b) the review of design and survey during and after construction to verify*

*compliance with such Rules, guides, standards or other criteria c) the assignment and registration of class when such compliance has been verified.*

*The Rules and standards are developed by Bureau staff and passed upon by committees made up of naval architects, marine engineers, shipbuilders, engine builders, steel makers and by other technical, operating and scientific personnel associated with the worldwide maritime industry. Theoretical research and development, established engineering disciplines, as well as satisfactory service experience are utilized in their development and promulgation. The Bureau and its committees can act only upon such theoretical and practical considerations in developing Rules and standards."*

### 2.2.4 Regulatory Agencies

The Canadian oil industry is controlled by Acts of Parliament that are administered by the Canada Oil and Gas Lands Administration (COGLA).

Authority to drill in offshore areas administered by COGLA is governed by regulations and guidelines developed by the Offshore Structures Division.

These regulations and guidelines, for example the Canada Oil and Gas Drilling regulations (PC 1979-25 amended by PC 1980-2111), require that the operator have available a description of the environmental conditions in which a structure will operate and survive and that the structure and operating system be suitably designed.

The above noted regulations state, for example, (PART I, 8.(f),(ii)) that any person applying for a Drilling Program Approval furnish information on *"The prevailing environmental conditions in the area of the program"* and *"in the case of every drilling unit used or intended to be used by an applicant during the program, (i) the data and particulars on which the applicant relies to show that the drilling unit has adequate stability to safely conduct the proposed program, and (ii) the details of the structural design of the drilling unit on which the applicant relies to show that the drilling unit has strength adequate to withstand conditions of extreme loading caused by a combination of the most unfavourable functional and environmental loads".*

In order to administer these regulations and guidelines COGLA or its agents must have knowledge of the wave climate of the areas where activities are taking place in order that it may ensure that the owner or operator has submitted an adequate description of the wave climate. In some countries the regulatory agency has had guidance notes developed which contain a description of the wave climate of selected areas. Neither such guidance notes nor the basic information required to compile them have been developed in Canada.

### 2.2.5 Research Organizations

The requirements of research organizations are different from those of the other groups.

The designer, owner or operator, classsification society and regulatory bodies are primarily concerned with the state of the art of design as it is

published in manuals of recommended practice, in codes of practice, in classification rules and in regulations.

The research organization, in cooperation with these other organizations, is concerned with the development of improved practices, codes, rules and regulations and in undertaking the necessary research and engineering studies to support this development work. Their objective is to achieve safer, more efficient and more cost effective structures that will support the exploration and recovery of hydrocarbons. The research organization is generally pushing the scientists and engineers to advance the theory relating to waves and provide more complex descriptions of the sea-state.

The classification societies have research departments within their own organization and some design companies and owners employ highly qualified engineers whose role is to contribute to current research and development efforts.

## 2.3 Summary of Requirements for Wave Data

The requirements of the organizations described in Section 2.2 were determined by review of published reports and by discussion with representative companies (reported in Section 2.4).

The review of published reports placed emphasis on design manuals that describe procedures and methodologies accepted by the industry rather than on texts or conference proceedings that have not received review and acceptance by the industry.

The available reports describe procedures that cover many topics. Procedures that require, or use wave data have been extracted and are presented in Appendix A. In this section the wave data that are required in following these procedures are summarized.

The reports referenced in Appendix A differentiate between the design of structures fixed to the ocean floor and mobile structures. For fatigue analysis or the design and assessment of operations this differentiation is not so important.

Consequently, Appendix A is divided as follows:

| | |
|---|---|
| A-1 | Survival in extreme conditions |
| A-1-1 | Fixed structures |
| A-1-2 | Floating structures |
| A-2 | Fatigue analysis |
| A-3 | Operational assessments |
| A-4 | Requirements of Regulatory Agency |

The design of structures to survive in extreme wave conditions may involve either deterministic or stochastic forms of analysis.

In a deterministic analysis the stress produced in components of the structure or the response to a defined wave height and period is calculated. The wave height (and associated period) used in the calculation is generally the most probable maximum wave height with a return period of 100 years.

In a stochastic analysis a probability distribution function of stress in a component of the structure or of the response of the structure to a sea state described by a wave spectrum may be calculated. The wave spectrum may also have a return period of 100 years. This wave spectrum may be determined from a study of the waves in the area. If not and if deemed appropriate, one of the standard spectral forms such as JONSWAP or Peirson-Moskowitz can be used.

In practice, the deterministic approach is frequently used for structural analysis while the stochastic approach is generally used for calculating motion response. A stochastic analysis is a calculation in the frequency domain. Analysis of structural response to irregular waves may also be completed in the time domain if the water surface profile is defined and the velocity and acceleration fields below the surface are estimated. Time domain analysis is recommended for calculations that are drag force dominated as are required for guyed towers.

Design for survival in extreme conditions may require knowledge of the most probable maximum crest elevation, with a defined return period, to ensure a wave does not impact with the upper deck of a structure. This crest elevation must be determined from a knowledge of the tidal regime and the probability of occurrence of storm surges as well as the maximum wave height.

Fatigue anaylsis requires information on the frequency of occurrence of stress above a threshold level during the life of the structure and therefore requires a statistical description of the wave climate rather than just a knowledge of extreme events.

Design and assessment of operations may involve a knowledge of the motion response of the structure and its support vessels, of the response of diving equipment or of the response of the structure while being towed, to give some examples. However, operational concerns all require a detailed description of the wave climate of the area where the structure will operate.

The required wave data can be summarized as follows:

### For Deterministic Analysis

Most probable maximum wave height for selected return period (typically return period of 100 years).

Wave periods that are associated with the selected wave height (analysis should be undertaken for the wave period that produces the largest load on or response of the structure).

Analysis will consider lower wave heights for cases where the wave period associated with lower heights will cause larger stresses or response (than the wave periods associated with the larger waves). For structures where the orientation is fixed, it is necessary to define these extreme wave conditions by direction.

### For Stochastic Analysis

A variance spectrum for selected return period (typically return period of 100 years).

Shape or formulation of wave spectrum and peak period (or other period parameter should be varied while maintaining the same characteristic wave height (significant wave height) in order to produce largest loads or response that could occur.

Analysis will consider lower wave heights for cases where the wave periods associated with lower heights will cause larger stresses or responses.

For structures where the orientation is fixed it is necessary to define these extreme wave conditions by direction.

### Underdeck Clearance

Most probable maximum crest elevation for selected return period (typically return period of 100 years). This elevation must consider the

elevation of the mean water level that is expected to occur during this event. This is influenced by the tide, atmosphere pressure, wind set-up etc.

### Fatigue

Bi-variate frequency of occurrence (scatter) diagrams of wave height and period parameters (typically characteristic wave height and peak period) by direction. These diagrams may represent twenty years of data.

### Operational Design and Assessment

Requirement is for description of the sea-state (e.g. characteristic wave height, peak period and mean direction) at regular intervals (e.g. 3 hrs) throughout a 3 to 5 year period from which many statistical presentations (such as exceedence and persistance diagrams) can be developed.

Model testing in hydraulic laboratories are, for some designs, an important part of the design process to determine stability and motion characteristics. Typically, an instrumented model of the structure is subjected to simulated wave action in a basin. Either pressures on the model or the strain in selected members can be measured or the response of the structure can be monitored.

The requirements of model testing programs for wave data depends largely on the capabilities of the laboratory to generate waves. However, some laboratories have now developed capabilities to reproduce almost any form of defined sea-state. The scientist, engineer and instrument development companies are as a result being challenged to provide accurate, complex descriptions of the sea-states to which the structure will be exposed.

## 2.4 Interviews with representative Organizations

During the course of this investigation, meetings were held with a number of organizations. The objectives of these meetings were as follows:

- to obtain an overview of the design, classification and regulatory processes as they apply to the structures used for the exploration and recovery of oil and gas.

- to identify the specific requirements of design, classification, regulatory and research organizations for wave data.

- to identify any outstanding problems associated with the design, classification and regulation of structures designed for the exploration and recovery of oil and gas that can be attributed to a lack of data or knowledge concerning wind generated waves and their effects on structures.

Meetings were held with representatives of the following organizations:

Design:

- Submarine Engineering, Aberdeen
  (T. Haavie, J. Dalgleish, W. Wagstaff)

- Early and Wright, San Francisco
  (M.L. Griesert, M. Praught)

- National Maritime Institute Ltd., London
  (N.M.I. provides an analysis service to designers)
  (R. Standing, N. Hogben, L. Dacunha)

Owner:

- PetroCanada Resources
  (G.T. Glazier by correspondence)

Classification:

- American Bureau of Shipping, New York
  (S. McIntyre, H.H. Chen, B. Liu)

- Det Norske Veritas, (Meeting in Ottawa)
  (J. Gorman)

Regulation:

- Canada Oil and Gas Lands Administration, Ottawa
  (R. Smith, T. Starr, F. Jackson, Y. Madsen, K. Sato, L. Muir)

Research:

- National Research Council of Canada, Ottawa
  (J. Ploeg, E. Funke, G. Mogridge, E. Mansard)

- Hydraulic Research Ltd., Wallingford
  (S. Huntingdon, A. Brampton, J. Weare)

- National Maritime Institute Ltd., London
  (NMI also undertakes research)
  (R. Standing, N. Hogben, L. Dacunha)

- Institute of Oceanographic Sciences, U.K.
  (J. Ewing, L. Draper, P. Challenor, D. Carter)

- American Bureau of Shipping, New York
  (The research program of ABS was reviewed with S. Mclutry, H.H. Chen, and D. Liu)

During the discussions with the various organizations it was confirmed that the industry follows the procedures summarized in section 2.3 and reported in Appendix A. Additional analyses may be undertaken, and frequently are, however, the summarized procedures represent the minimum requirements.

Similarily the wave data requirements outlined in section 2.3 also represent the minimum requirements for wave data, even though some organization may attempt to obtain more detailed information.

All organizations discussed the need for improved or additional data in Canada. The urgency with which the data should be obtained depends on the location under consideration, the type of structure and the responsibilities of the organization.

None of the design, classification or regulatory agencies identified any limitations of existing methods for obtaining wave data, of analysing wave data, or of applying wave data to design procedures that lead to unsafe structures, structures that are significantly over designed, or problems with operation of these structures.

Important research and development work in the area of wave measurement and prediction and wave-structure interaction is continuing. However, this research is not driven by a sense of urgency that disasters will occur if the work is not completed quickly.

It is generally felt that the design of structures for exploration and recovery of hydrocarbons is satisfactory when measured against other industries. For example Hammett (1983) reviewed the performance of semi-submersible drilling units. He notes that the petroleum industry has more than 1600 rig-years experience in using semi-submersible drilling units. In that time approximately 6,000 wells have been drilled which involved more than 130,000 man years. Semi-submersible drilling units have been subjected to 100-foot wave conditions, have continued drilling in 40-foot waves, and have transited over 1,000,000 miles in all kinds of sea-states. Hammett (1983) provides the following information on casuality rates.

Total loss for Mobile Offshore Structures and Merchant Ships in Worldwide Operation (1970-1976)

| Type of Vessel | Casuality Rate (Loss of units per 100 Vessel-Years) | |
|---|---|---|
| Mobile Rigs | 0.9 | |
| Jackups | | 1.4 |
| Semi-submersibles | | 0.3 |
| Barges | | 0.5 |
| Merchant Ships | 0.7 | |

The discussions with the various organizations produced many facts and recommendations that have been incorporated into the text of this report. Some of these points, which in the authors opinion should be highlighted, are noted below. These points are mainly concerned with recommendations or requirements for studies of waves and structure response to wave action.

Designers:

Earl and Wright noted the variation in the magnitude of the extreme wave conditions throughout the study area and stressed the need to have extreme waves, winds and currents for each of the many different parts of the study area.

Earl and Wright also noted that for operational planning it is desirable to have in the order of five years of simultaneous measurements of waves, winds and currents.

Submarine Engineering provided considerable information on current design procedures. A concern with the lack of information and design procedures addressing wave steepness and wave grouping and the resulting effect of these phenomena on a structure was noted. The need for improved design procedures and regulations addressing wave induced drift forces and tilt was also noted. Submarine Engineering stressed the requirement for continuous simultaneous measurements of waves, winds and currents for the assessment of operations.

Owners:

PetroCanada presented a valuable statement on current practice that is reflected in this report. The benefit of a measurement and research program that has the object of verifying appropriate statistical wave height distributions for East Coast storms of various intensities and durations, in order to provide confidence in extreme wave heights, was noted.

PetroCanada commented, when referring to wave data available in the study area that *"The data available are adequate for design procedures presently in use. However if higher quality or different data were available, then engineering practice could be enhanced to use the better data."* The conclusions of this report are in variance with this comment. This report concludes that the available data do not provide a reliable description of the

wave climate of the study area and are insufficient for the estimation of extreme events.

**Classification Societies:**

The American Bureau of Shipping (ABS) expressed general satisfaction with the current design methods that are reported in Appendix A.

ABS noted that a number of items are being studied and reviewed by their Research Department. These items include:

- non linear effects in calculations of response of structures to waves
- time domain analyses
- effects of waves and currents on structures and wave-current interaction
- extreme wave conditions
- directional spectra

**Regulation Agencies:**

The Canadian Oil and Gas Lands Administration (COGLA) provided valuable insight into their concern with operations and the requirement of wave data for the assessment of operations. The effects of waves (and currents) on diving operations associated with oil and gas structures and the dependency of many activities on the timely completion of diving operations was noted. The relationship between quantities of consumables to be stored on a structure with the duration and frequency of downtime was stressed. Wave data is essential to the downtime calculations.

**Research:**

The National Research Council (NRC) are concerned with the true simulation of prototype sea-states in a wave basin designed for model testing of structures. NRC are investigating the variations in structure response to many phenomena such as wave grouping, wave steepness, and extreme wave heights. NRC stress the need for improved prototype measurements of waves to support this work and to eventually assist in the incorporation of the results of this work in engineering design procedures.

The Hydraulic Research Station, U.K. (HRS) noted the requirement to evaluate the response of some structures to waves in the presence of a current. HRS have also demonstrated that some structures have a critically different response in a directional sea-state than in uni-directional long crested waves.

The National Maritime Institute, U.K. (NMI) noted that current design procedures provide satisfactory results for the design of offshore structures. NMI are investigating the following items in their continuing research:

- low frequency response of structures

- free surface kinematics

- response of structures to waves in the presence of a current

- response to directional sea-states

The Institute of Oceanographic Sciences, U.K. (IOS) provided considerable background to wave related concerns in the U.K. The comments are contained in this report. An item of research that is of concern to this study area is the prediction of mean water levels that could be associated with the peak of the design storm (of perhaps 100 year return period). The design wave height is added to this mean water level to obtain the maximum crest height which some structures might encounter.

## 2.5 Currents and Winds

From an engineering perspective waves cannot be treated in isolation from currents and winds.

In the design of a structure it is the total load on the structure, or one of its members, that must be considered. Consequently, the current and wind conditions that will exist at the same as the selected wave conditions should be known.

In the assessment of operations, data on wind, currents, reduced visibility, etc. should be available as well as wave data, as it may be a combination of events that lead to unsafe conditions or a closing down of an operation. The duration of downtime of a particular operation may depend on all of these environmental parameters. For example, currents are likely to be a very important phenomenon, in addition to wave action in restricting diving operations.

### 2.5.1 Design

For the design of a structure the publications referenced in Appendix A stress the need for complete environmental data.

API 1982 states that *"the tides, currents and wind which potentially occur simultaneously with the wave trains producing the extreme events"* should be developed. It further states that *"environmental loads should be combined in a manner consistent with the probability of their simultaneous occurrences during the loading conditon being considered"*.

ABS 1983 notes that the most severe environmental conditions will normally be composed of *"The maximum wave height correspondence to the selected recurrence period, together with the associated wind, current and limited water depth, and appropriate ice and snow effects"*. It also notes that consideration should be given to permutations of the combinations of these events, and that the recurrence period of the (total) event is normally not to be less then one hundred years.

It is clear that presentation of extreme wave data for design purposes requires a description of the current and wind that will occur at the same time. In fact it is desirable that a number of combinations of waves, winds and currents be considered where the return period of the joint event of three occurences is 100 years or more.

### 2.5.2 Operations

The data required for complete assessment of operations is simultaneous observations of waves, currents and winds and, desirably, other phenomena such as visibility, ice, and air temperature. These observations should be made continuously over a period in the order of three to five years.

### 2.5.3 Current and Wave Interaction

Waves propagating in a current may be significantly influenced by the current to the extent that steepening and breaking of the waves may be

induced. Variations in surface currents may also cause refraction, a pnenomenon where wave energy is concentrated in certain areas and dispersed in other areas. Consequently, any definitive study of the wave climate of a selected area requires a knowledge of the currents that occur in that area.

In this investigation the quality and availability of wind and current data that are required by the design, classification and regulatory organizations have not been investigated.

## 3.0 Available Wave Data for Eastern Canada Study Area

This section discusses and assesses the three major types of wave data available for the study area.

Section 3.1 discusses instrumentally measured wave data. Section 3.2 discusses visually observed data from ships of opportunity. Section 3.3 discusses the "hindcast" datasets which are produced by using computer models to estimate waves from time series of historical wind speeds and directions.

## 3.1 Instrumentally Measured Wave Data

### 3.1.1 Characteristics of Instrumentally Measured Wave Data

Extensive measurement of waves has been undertaken in Eastern Canada since 1970 primarily by the Marine Environmental Data Service (MEDS) of Fisheries and Oceans. Much offshore data has been acquired through cost shared programs between MEDS and the oil companies operating the drilling units. The Datawell Waverider buoy has been used as the wave sensing instrument. The Waverider consists of an accelerometer housed in a 0.7 or 0.9 metre diameter floating sphere that is tethered with a single point mooring. In normal operation the vertical travel of the buoy is measured as a function of time for twenty minutes every three hours and from this record various parameters describing the sea state can be determined. No information on wave direction is provided by this system.

Waves have been measured using other methods, but compared with the Waverider measurements few records obtained by other systems exist. Wave records have been obtained by measurements obtained with radar systems mounted in satellites, with fixed staffs mounted on piers in coastal areas, and since 1983 using a buoy capable of measuring wave direction.

It is estimated that approximately 219,000 twenty minute records have been obtained with the Waverider buoy within the study area. These records can be categorized as follows:

- measurements made close to the shoreline in support of the design of harbour or coastal structures. These amount to approximately 45 per cent of the available records and have little use to the oil and gas industry;

- measurements made at coastal locations to provide long term wave statistics. These records also have limited application to the oil and gas industry;

- measurements made during oil and gas exploration activities in the cooperative ventures between MEDS and the operators. These amount to approximately 62,330 records or 28.5 per cent of the available data. The measurements provide information on wind generated waves in areas where exploration is proceeding.

The standard parameters used to describe the magnitude of the wave conditions are the characteristic (or significant) wave height and the peak period. These variables are obtained from a variance spectrum analysis.

Common parameters used to describe the sea state and analysis procedures are described in section 2.1 of this report.

There is no doubt that the available recorded wave data are, and will be, invaluable to engineers and oceanographers concerned with exploration for recovery of hydrocarbons. However, these data provide only intermittant coverage for relatively short periods at any one location. In addition an absolute measurement of the wave profile is not obtained because the buoy has little lateral restraint. As stated above no information is provided on the direction of wave travel.

As discussed in earlier sections of this report, it is clear that the ultimate wave record for a location where recovery of oil or gas is to take place would be at least one hundred years in length and would include wave direction information and a relatively complete and accurate description of the water surface profile. A twenty year time series is the minimum required for the reliable prediction of extreme events for the oil industry. Non-directional wave measurement on Canada's east coast began in ernest with hydrocarbon exploration in the early 1970's. Directional measurements began only in 1983 and are as yet not proven to be reliable. Absolute measurements of the surface profile on a scale suitable for the development of climatological descriptions of the parameters over a significant ocean area are not feasible at this time.

Consequently, the available measured data do not provide a basis from which reliable estimates of the required wave climate parameters can be obtained. The measured series are too short and do not include all necessary variables.

One of the primary uses of these data is for the verification of numerical procedures for estimating wave conditions from known meteorological conditions. These wave prediction (or hindcasting) procedures are discussed in section 3.5.

The fact that the existing data have been obtained only during exploratory programs means that data are not available for areas where exploration is about to start. The existing data may be limited because the measurements are confined to the exploratory drilling season and do not provide coverage during the most severe part of the year, a period to which permanent structures would be exposed.

Remote sensing techniques have been used to measure waves from satellites or aircraft. These techniques are even more recent than the Waverider measurement program and the time series are therefore shorter. The techniques involve the use of laser altimeters and sophisticated radars. To date only the laser altimeter has been proven capable of producing accurate results on the continuing basis required to develop climatological data sets. The laser altimeter produces only a wave height value and does not measure periods, directions on wave profiles.

Details of the available recorded wave data that have been obtained in the study area are provided in the following sections.

### 3.1.2 Availability of Instrumentally Measured Wave Data

The majority of wave records of interest to this study have been obtained and archived by the Marine Environmental Data Service (MEDS), Fisheries and Oceans. Other organizations that have obtained wave records are the National Research Council of Canada and the National Oceanic and Atmospheric Administration (NOAA) (satellite data). These data are described in the following sections. All of the data described are archived by MEDS either in digital or report form.

#### 3.1.2.1 MEDS Holdings

MEDS has been largely responsible for the retrieval, analysis and presentation of all wave measurements undertaken in Canadian waters since 1970. Wave data have been obtained at over 200 locations using buoys, staff gauges and pressure cells.

The locations where MEDS has obtained wave data within the study area are shown in Figure 3.1. The period of coverage for each location is provided in Appendix C.

The standard product available for each of the indicated locations are various presentations of the characteristic wave height and peak period obtained at 3 hour intervals when the characteristic height is less than 4 meters and every 20 minutes when greater then 4 meters. Many other products and statistical presentations are available and these are described in MEDS publications. The variance spectrum for each wave record is also archived.

As stated the data of interest to this study were obtained using the Datawell Waverider buoy. These buoys are calibrated by MEDS before and after deployment and the estimates of wave heights are considered to be accurate to within 3 per cent.

The Waverider buoys move in an approximately circular motion restrained by its single point mooring. Consequently, the resulting water surface profile is not exactly the same as that measured by a fixed staff. This is a limitation of the Waverider data to some engineering applications.

#### 3.1.2.2 NRC Wave Study

A wave climate study of the Great Lakes and Gulf of St. Lawrence was completed by the Hydraulics Laboratory of the National Research Council during the three year period 1965-1967, Ashe and Ploeg (1968). Wave records were obtained with accelerometer buoys at ten locations in the Gulf of St. Lawrence as shown in Figure 3.1. The results of this study are presented in Ashe and Ploeg (1968). They include listings of the characteristic wave heights and periods obtained at each location.

#### 3.1.2.3 NOAA Satellite Data

Several NOAA satellites have had on board a laser altimeter device with the capability to measure significant wave height. Only the data from the SEASAT satellite which operated from July to October 1978 has been acquired, assessed and archived by MEDS. These data have not played a part in the development of knowledge of design conditions or wave climate

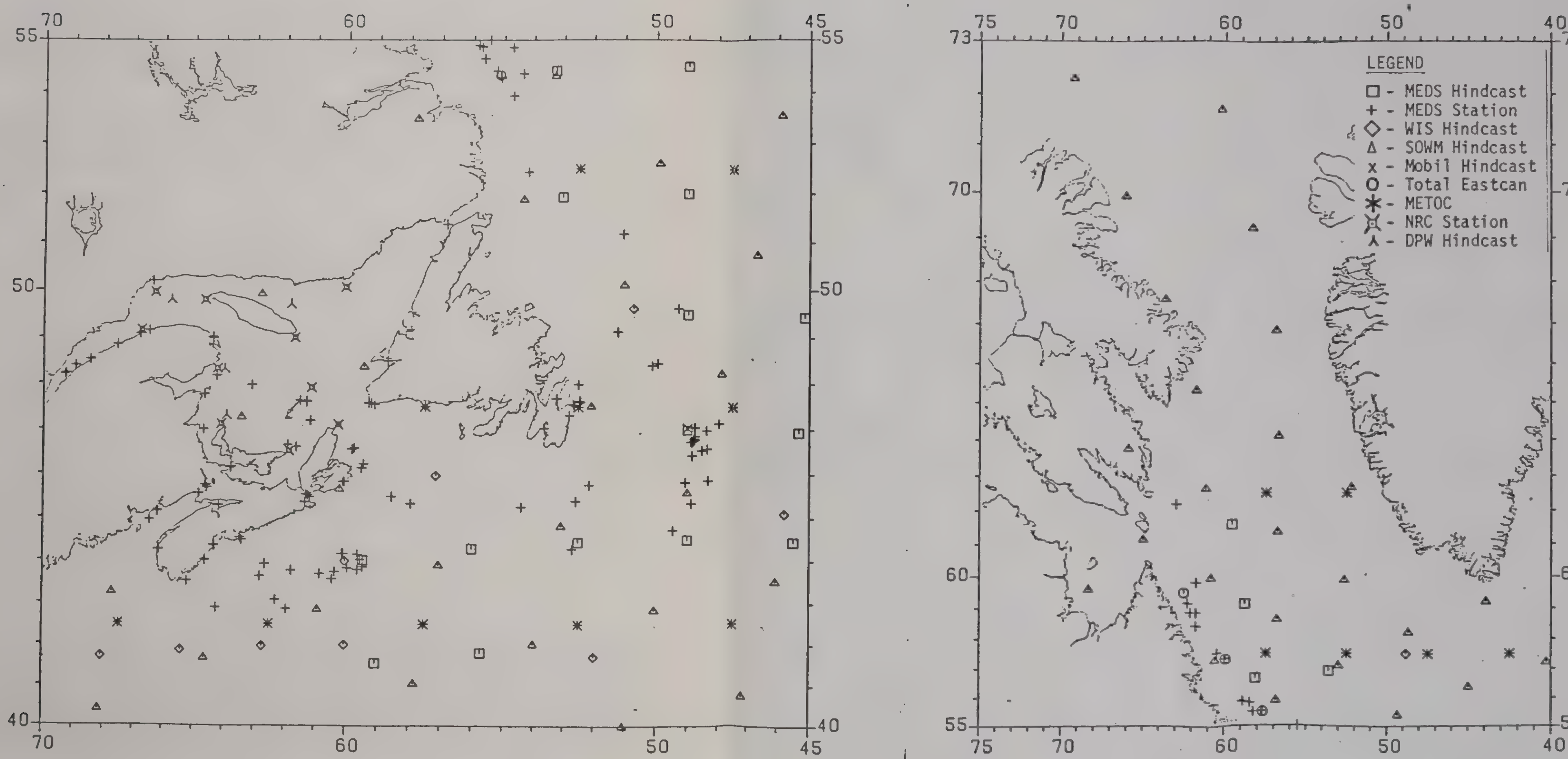



Figure 3.1 Map of Wave Data Locations.

statistics due to their short time series and the limitations of the measurement to significant wave height only.

### 3.1.3 Assessment of Instrumentally Measured Wave Data

#### 3.1.3.1 MEDS Measured Data

The data collected by the joint MEDS-industry programs in association with exploratory drilling is considered to be of excellent quality. The calibration procedures for the instrument and the control applied to the data conform to accepted scientific practice. However, the spacial and temporal coverage are acknowledged to be limited and wave direction is not measured.

When and where the data exist they are suitable to be considered the standard for evaluation of the performance of other methods of determining the wave spectrum, the characteristic wave height and the period of the most energetic frequency band in the wave field.

#### 3.1.3.2 NRC Wave Study

The data from the NRC wave study were obtained with first prototype accelerometer buoys and are not considered to be as reliable as the Waverider data. The same comment regarding spatial and temporal coverage applies.

#### 3.1.3.3 NOAA Satellite Data

The data from the SEASAT satellite was evaluated against the measured data held in MEDS for the periods and locations where coincidences of measurement occurred. The results indicated the SEASAT data were accurate to within 10% and therefore would be valuable from a wave climate perspective if sufficient spatial and temporal coverage were available.

The temporal coverage is of course not available since the satellite only lasted a little over 3 months. The spatial coverage of such a satellite would approximately match the number of observations available from the merchant fleet of ships reporting visual wave observations. (RA Jones, personal communication).

## 3.2 Observations by Ships Officers

### 3.2.1 Characteristics of the Shipboard Observation Data

Observations of wave conditions as well as meteorological phenomena are routinely made by merchant shipping. From many ships these data are transmitted to various agencies where they are sorted, edited and archived. Data obtained since the early 1900's have been archived and used by some agencies. The majority of the data are, naturally, concentrated along the major shipping routes.

The ships officer is required to estimate and report the significant height and significant period of the locally generated waves as well as the significant height, significant period and direction of the swell. The significant height is defined as the average height of the larger well formed waves, and the significant period as the average period of these waves.

### 3.2.2 Availability of the Shipboard Observation Data

Ship observation data covering the study area can be obtained from the U.S. National Climatic Center in Ashville, North Carolina or from the UK Meteorological Office, Bracknell (U.K. data are also available in synthesized form from the National Maritime Institute).

Data from the U.S. National Climate Center are summarized in publications entitled "Summaries of Synoptic Meteorological Observations".

The Atmospheric Environment Service (AES) of the Department of the Environment has acquired the visually observed data and has provided a copy of the east coast observations to MEDS.

### 3.2.3 Assessment of the Shipboard Observation Data

Many researchers, for example Hoffman et al. (1978), Chen et al. (1979), Cummins and Bales (1980), Andrews et al. (1983), and Hogben and Lumb (1967), refer to limitations of ship observation data. The data are considered to have limited reliability because the estimates are made by different observers with different backgrounds and training, while standing at different elevations on moving ships in varying conditions of weather and visibility. The main limitation of the data, other than the observer bias, is the fair weather bias that results from the tendency of ships to avoid storms. Observations of wave period are considered by most investigators to be particularly unreliable.

Comparisons between reported visual observations and the significant wave height from recorded data show considerable scatter, as illustrated in Figure 3.2 from Hogben and Lumb (1967). Relationships between the significant wave height from an instrument recording a visual observations of wave heights and periods have been developed by many investigators including Hogben and Lumb (1967), Nordenstrom (1975), Jardine (1979), and Ochi (1978). The variation between these relationships is illustrated in Figures 3.3, 3.4 and 3.5 from Andrews et al. (1983).

Andrews et al. (1983), describe 'considerable divergence' between these developed relationships for the higher values of wave height and period and note 'that estimates of extreme wave height based on visual observations of height alone may be subject to considerable uncertainty'.

On the other hand it has been noted by Captain Blackham of Noble Denton, UK (personal communication) that the assumption of a fair weather bias many not be justified in certain areas off the Canadian east coast. He points out that storm avoidance can be made difficult because of the geography of the area and because of the economic implications of remaining in port to wait out a storm or steering a longer course around it. He has also pointed out that the ships reporting visual observations are generally large and designed to weather the most severe Atlantic storms.

Wilson (1983) reported on a comparison of a variety of wave datasets for the Newfoundland Grand Banks. The comparison failed to produce evidence of a fair weather bias in the visually observed data. However, it is known that the database has in it a certain amount of erroneously coded data. It could not be concluded with certainty that these erroneous data did not offset the fair weather bias.

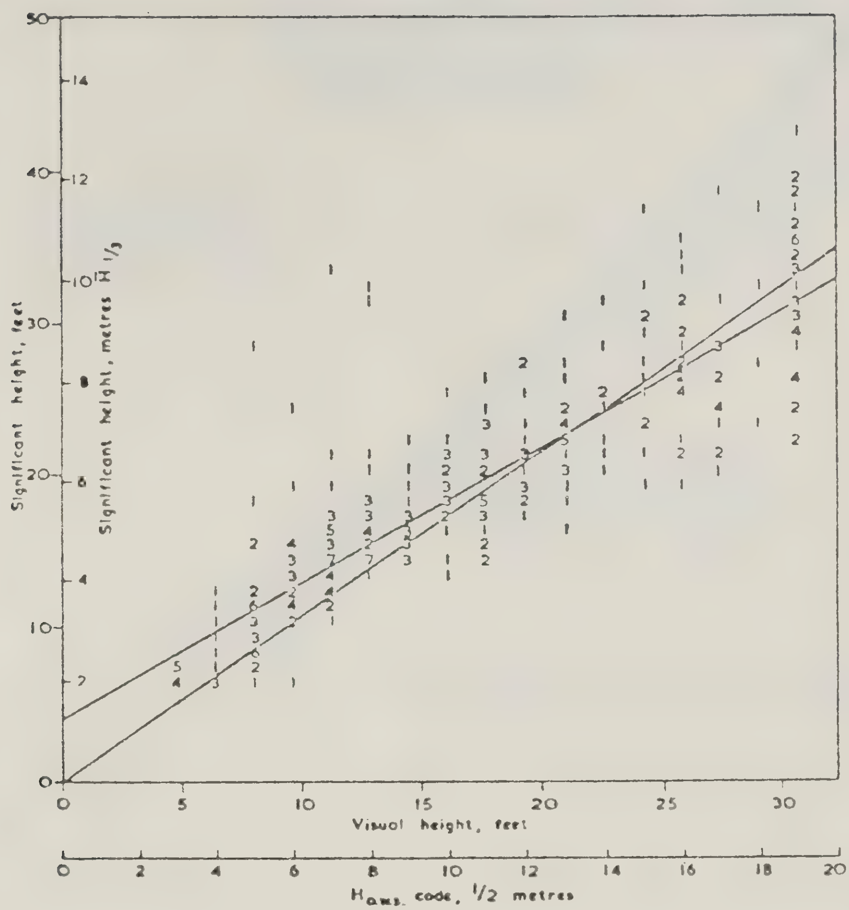



Figure 3.2 Comparison of Measured Significant Wave Height Versus Visually Observed Height (Hogben and Lumb, 1967).

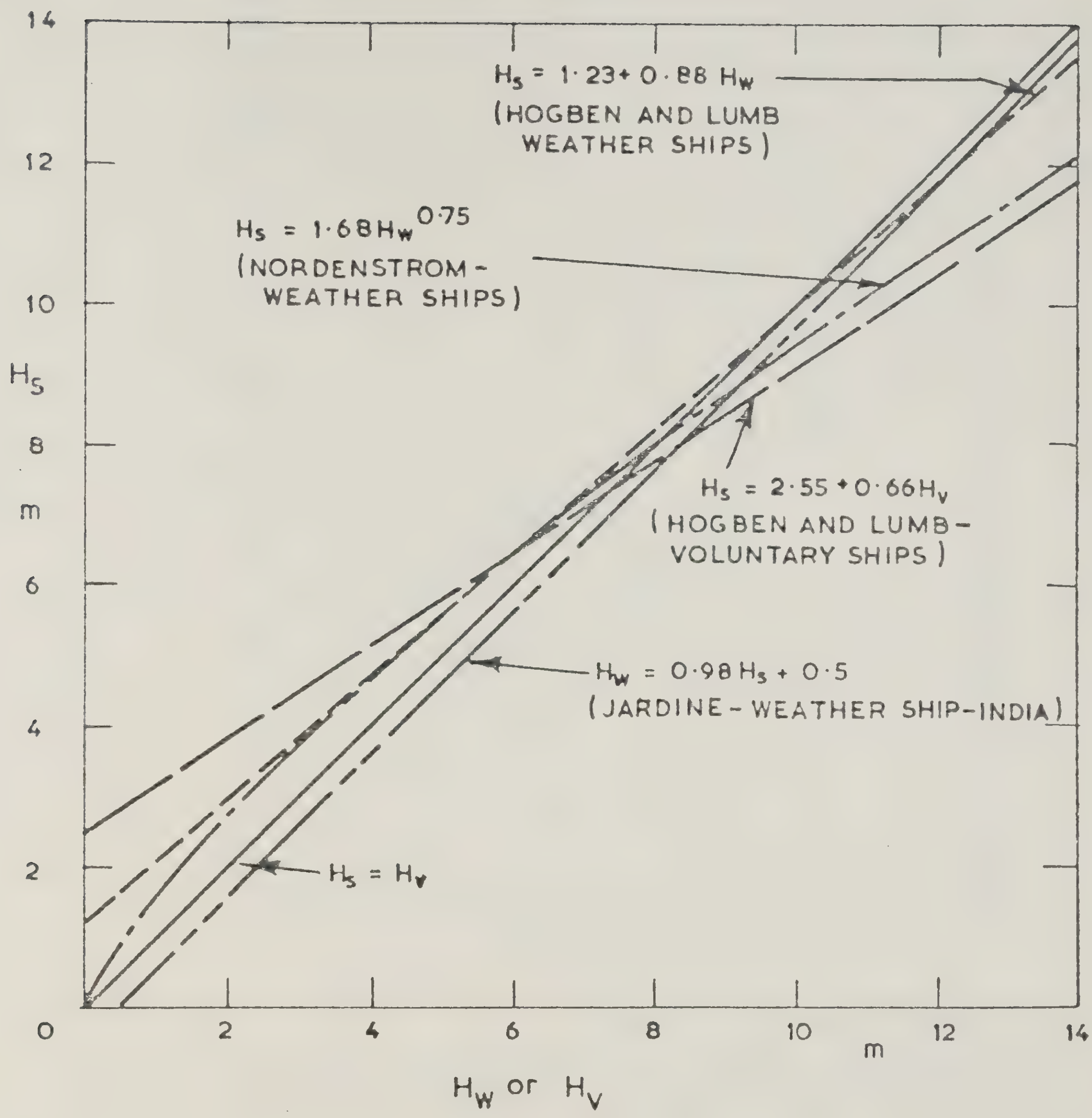



Figure 3.3 Comparisons of Instrumental and Visual Wave Height Observations (Andrews et al., 1983).

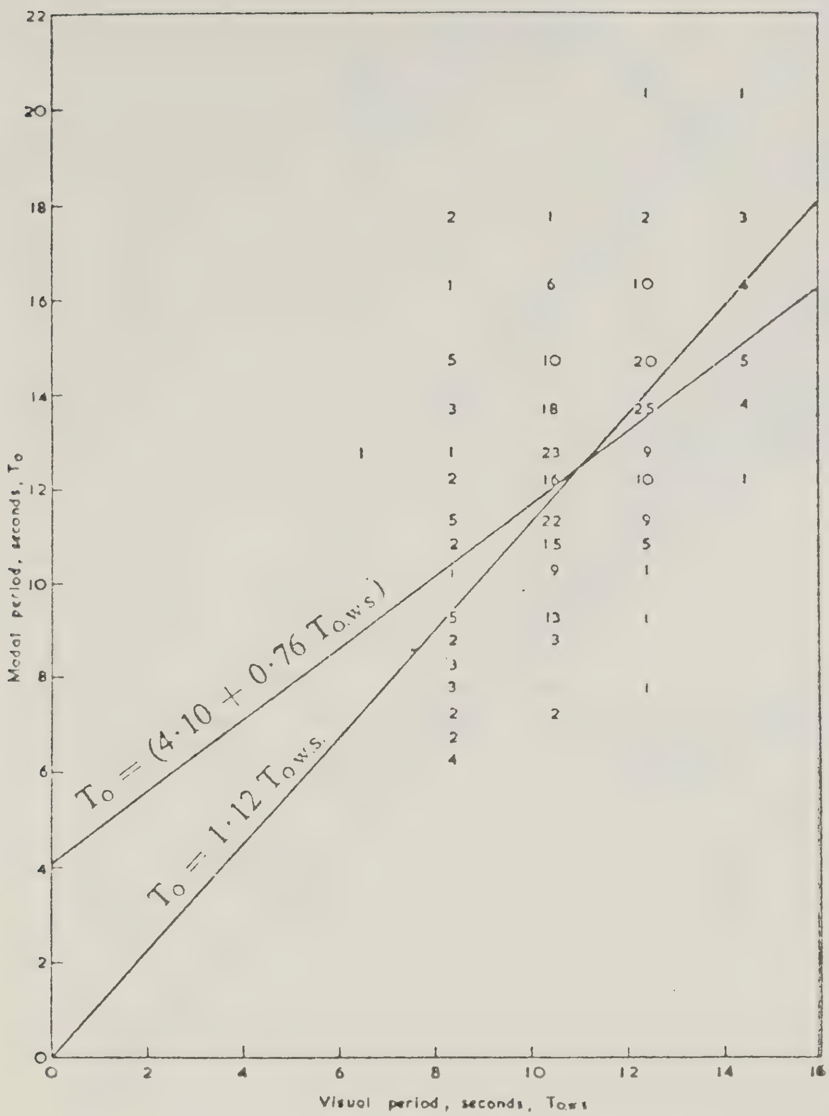



Figure 3.4 Comparisons of Instrumental and Visual Wave Period Observations (Andrews et al., 1983).

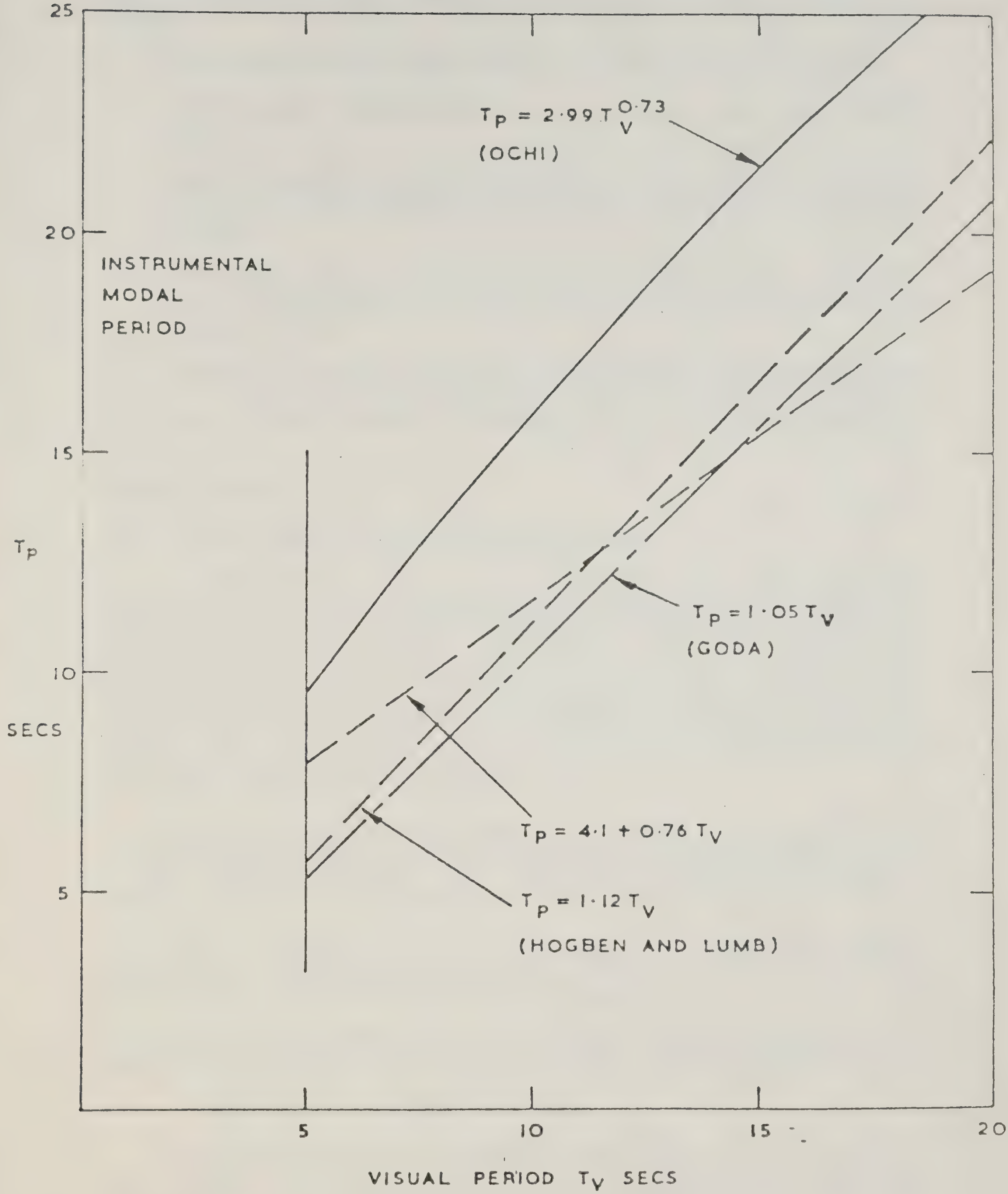



Figure 3.5 Comparison of Visual and Modal Wave Period (Andrews et al., 1983).

A more thorough study of the visual observed wave data including further quality assessment and intercomparisons with hindcast and measured data is in progress in MEDS. However, that study will not produce results until mid-1984.

The limitations of ship observation data can be summarized as follows:

1. There is limited coverage for areas not covered by the major shipping routes.

2. From an engineering point of view the description of the sea state is limited since wave spectra are not available and the observed period is unreliable.

3. The observations are not considered, at this time, to be sufficiently precise for estimating the extreme events required for the design of ocean structures.

The METOC data set and the NMIMET procedure described in section 3.3. and 3.4 below are based on visual observations. In each case processing procedures have been designed to overcome some of the limitations described above.

## 3.3 METOC Wave Data

### 3.3.1 Characteristics of the METOC Wave Data Set

The METOC wave data set has been prepared from significant wave charts prepared twice daily by the Canadian Forces METOC (Meteorology-Oceanography) Centre in Halifax. The charts are prepared from ship observations supplemented with real-time Waverider buoy data from exploratory oil rigs and coastal locations. The observations and buoy data are further supplemented with data derived from estimated winds using simple hindcast procedures to fill gaps where no ship observations or Waverider data are available. This tends to overcome the limitation that the visual observations are concentrated on the major shipping routes.

The digital dataset has been obtained by manually abstracting values of wave height, wave period and wave direction from the historical wave charts for each five degree square. This work been carried out by the Bedford Institute of Oceanography and the Atmospheric Environment Service.

The main grid used in the abstraction consists of squares of five degrees latitude by five degrees longitude, except in coastal areas where the grid has been distorted to accommodate the coastal topography.

The wave predictions used in the preparation of the METOC chart takes into account ice conditions limiting wave generation and propagation.

### 3.3.2 Availability of the METOC Wave Data

The METOC charts cover the North Atlantic Ocean between 25 degrees north latitude and 70 degrees north latitude, excluding major embayments including the Gulf of Mexico, Gulf of St. Lawrence and Hudson Bay. The grid points applicable to the study area are shown in figure 3.1.

The wave height data abstracted for five degree squares by the Bedford Institute cover the the period January 1, 1970 to December 31, 1980. The period and direction data and the maximum significant height occurring in each five degree abstracted by the AES cover the period May 1, 1972 to December 31, 1980. These data sets have been integrated in a single magnetic tape by MEDS and are available from BIO, AES or MEDS.

### 3.3.3 Assessment of the METOC Data

The quality of this data set can be considered to be higher than that of the ship observation data from which it has been prepared. This is due to the subjective quality assessment carried out by the analysts while preparing the charts. The analysts can and do compare observations from nearby ships to identify errors and use the previous chart and the hindcasting nomograms to assess individual observations and fill data gaps.

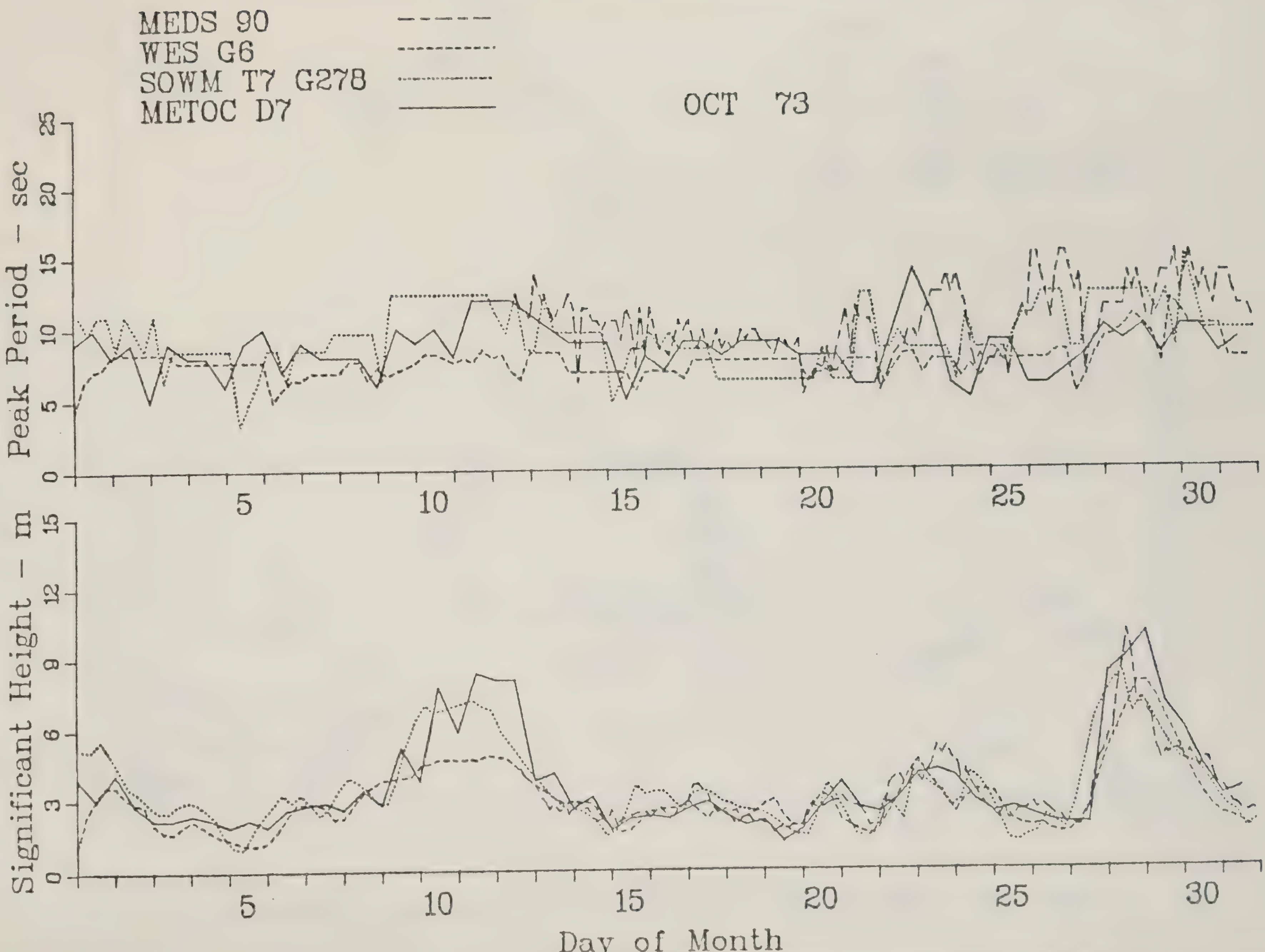
The METOC data have been compared to that produced by four of the five hindcast described in later sections. It is not possible to assess the METOC data against measured data since the measurements were reported to the Center and were used in preparing the charts. Therefore they must agree.

Figure 3.6 (Oct. 73) is a comparison of the METOC data with measured data, with a SOWM hindcast point and a WIS hindcast point in the vicinity of Hibernia. Figure 3.7 shows the locations of the wave data points used in this comparison and those others used in later parts of this section. The agreement is quite acceptable for operational concerns during the period October 13 to 31 when the measurements are available. During the period October 9 to 12 it is not clear which wave height is correct. Figure 3.8 (March 73) on the other hand is featured by a sharp disagreement between the data sets at another location near Hibernia. A review of the pressure analysis and the ice chart reveals the cause. The METOC data is in fact the more correct. The hindcasts produced large waves because the low pressure area generating the wind was located to cause a long fetch generating area extending NNW into the Labrador Sea. However the waves were not generated because a broad ice field extended from the Labrador Coast almost to Flemish Cap and severely limited wave growth. The ice limit was not included in the SOWM and WIS hindcasts.

Other comparisons to the hindcast datasets reveal that the METOC data frequently agrees with one or more of these while disagreeing with others. While there is no consistent agreement with the other data sets it can be said that the METOC data usually agrees better with the more carefully done hindcasts.

The Mobil Oil hindcast contained eight storms for the period 1970 to 1980. For six of these storms there were no measurements available for the preparation of the METOC charts and the data provides an independent check on the METOC data. Table 3.1 below compares the peak significant wave heights for each storm.

Figure 3.6 A comparison of several data sources for October, 1973.



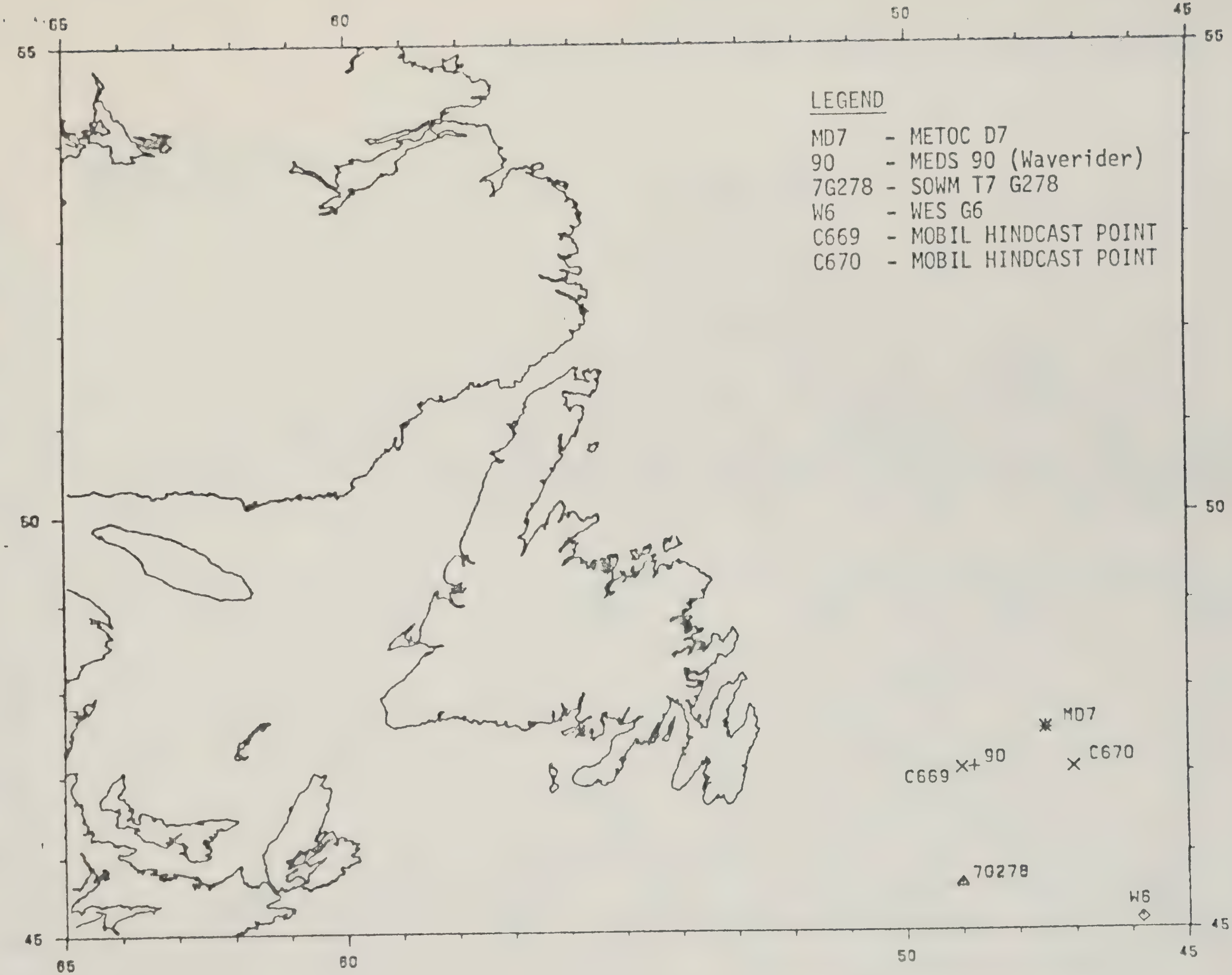
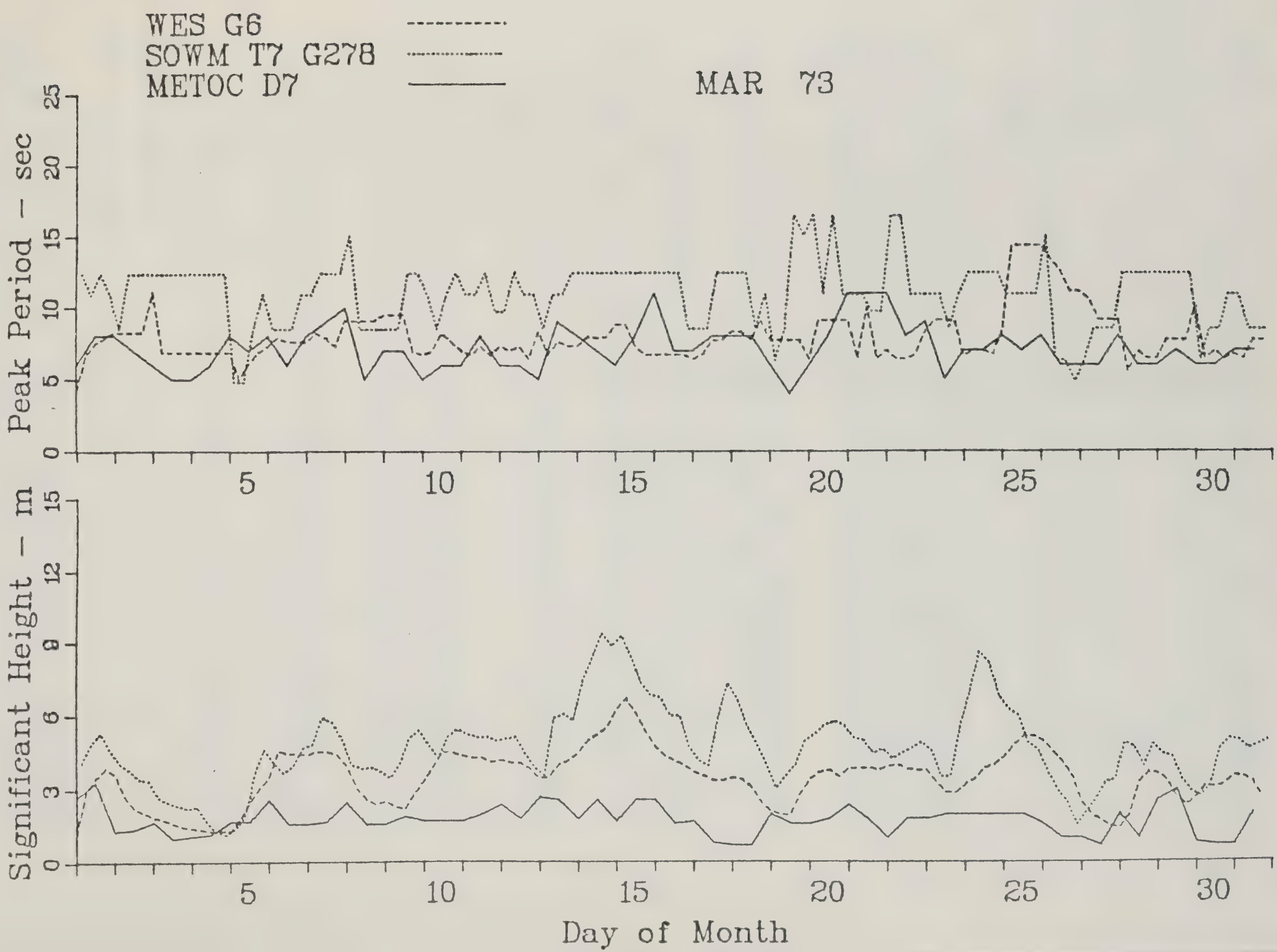



Figure 3.7 Locations of some of the wave data intercompared in this study.

Figure 3.8 A comparison of several data sources for March, 1973.



| Date | H 1/3 METOC | H 1/3 CARD 670 |
|---|---|---|
| March 4, 1978 | 11.5 | 10.9m |
| January 21, 1977 | 9.0 | 12.6m |
| March 18, 1976 | 9.9 | 10.6m |
| March 11-12, 1974 | 9.0 | 11.4m |
| January 17, 1971 | 6.1 | 12.5m |
| January 22, 1970 | 10.2 | 13.3m |

Table 3.1 METOC and Mobil hindcast maximum significant waveheights for six storms.

In assessing a dataset such as METOC the uses of the data must be kept in mind. There are essentially two applications for which the data can be used. The first is the determination of the wave climate for operational concerns. Examples of this would be the determination that the waves were larger than a given height for 30% of the time in February or that once the waves exceeded 6 metres at a given time of year they persisted above that height for 36 hours on the average.

It is concluded that in areas where there have been sufficient ship reports over the years and throughout the seasons of the year, the METOC data as published by Neu (1982) is good for these sorts of applications.

The second application for the METOC data would be in the estimation of return periods for extreme events. The estimation of an accurate return period depends on the accurate determination of peak wave heights for all the most severe storms. It is concluded that the METOC data is not as reliable for this application as a carefully prepared hindcast for the following reasons.

- the hindcast method used in preparing the charts in the absence of ship observation data is not nearly as sophisticated as that used in the better hindcast models.

- The personnel preparing the charts have less data and less opportunity to assess the developments of the winds in a storm than those preparing after the fact the hindcast input with a full history of the storm and the additional observation data which missed the cutoff in the real-time operations.

- the distribution of ships and the accuracy of their observations can not be expected to always be such as to pick up and produce accurate reports of the storm peaks.

- the suspected fair weather bias may be a factor in some or many circumstances.

## 3.4 NMIMET Procedure

### 3.4.1 Characteristics of the NMIMET Procedure

NMIMET is a suite of computer programs developed at NMI Ltd., Feltham U.K., in collaboration with the U.K. Meteorological Office, for the purpose of synthesising statistics of wave climates from visual observations of wave height and wind speed, or wind speed alone.

Extensive ship observations made in Canadian waters have been archived by the U.K. Meteorological offices. These observations are sufficiently numerous for the development of meaningful statistics only in the vicinity of major shipping routes. These data in their "raw" form contain many limitations as discussed in section 3.2.3.

In NMIMET a parametric model of the joint probability of wave height and wind speed is used as a best fit function for smoothing and enhancing the quality of the ship observations of waves. Inplausible observations are thus suppressed without subjective intervention.

Details of the models are contained in Andrew et al (1983).

Outputs from the model consist of scatter diagrams by season and directional sector where sufficient data exist. The frequency of extreme events can be estimated using either Weibull or log-normal techniques based on all the data. The use of this technique to estimate extreme events has not been theoretically justified and is considered questionable.

### 3.4.2 Availability of the NMIMET Data

The National Maritime Institute of the UK will produce, for a charge, an analysis of the ship observation data for anywhere the data are available. If the area of interest is off the major shipping routes it may be necessary to increase the size of the area in order to obtain sufficient observation data to produce a reliable synthesis.

### 3.4.3 Assessment of the NMIMET Analysis

The NMIMET procedure has been extensively assessed by the developers of the procedure against measured data in the vicinity of the UK. The results there were good for the exceedence of wave heights.

NMIMET data were obtained for three locations in the study area in order to obtain some experience with the data. It was expected that wave climate statistics (for example the wave height exceeded for 50 per cent of the year) would compare favourably with the METOC data and, possibly, the SOWM and WIS hindcast data for the more offshore locations. This was not found to be the case. These comparisons are presented and discussed in section 3.6. A verified source of data does not exist in the study area suitable for comparison with NMIMET data so it is not possible to draw firm conclusions as to the reliability of the NMIMET data. At this time these data can only be treated with caution as must the other datasets.

It is not expected, for the reasons discussed when reviewing ship observation and METOC data in general, that these data would be particularly suitable for the estimation of extremes. However, there is no suitable data available to either substantiate or disprove this expectation unequivocably.

## 3.5 Hindcast Wave Data

The sea state or the magnitude of the waves, on any body of water, can be predicted to a reasonably accuracy if the wind field over the water and its time history are known. The calculation requires a numerical model that should simulate the physical processes of wave generation by wind, wave

growth, wave-wave interaction, wave propagation and wave-current interaction and wave seabed interaction. If the physical processes are well represented by the numerical model, the reliability or accuracy of the prediction of the wave conditions is dependent on the accuracy of the description of the wind field over the generating area.

There are two categories of models. The simplest models represent an empirical approach that provides an estimate of the significant wave height and period, or similar parameters, and do not deal in depth with the physics of the problem. The other category includes the spectral models that describe the sea state by a directional variance spectrum. These models may include equations that deal with the spectral energy balance and the transfer of energy between wave periods (wave-wave interaction).

These latter models generally involve far more complex procedures than parametric models, and require relatively powerful computers.

In the simplest models, the wind velocity is assumed to be constant over the generating area, while in the complex models, the wind velocity is input at grid points over the generating area.

The accuracy of the latter model is partially dependent on the size of the grid and time interval between the wind velocity data. The wind data for the grid are determined from pressure gradients, although in some instances, these may be blended with winds obtained by other means. A more complete discussion of the state of the art of methods for sea state prediction is contained in Cardone and Ross (1977).

Many wind-wave hindcasts, which are based on historical wind data, have been undertaken for specific sites and have limited use for other areas. Two exceptions in the study area are hindcasts completed by the U.S. Navy, and the U.S. Army Corps of Engineers.

The U.S. Navy Fleet Numerical Oceanographic Center undertakes continuous wave forecasts using a spectral model of the oceans of the northern hemisphere. Of particular interest to this study, is a 20-year hindcast of the North Atlantic, completed with the U.S. Navy Spectral Ocean Wave Model (SOWM). These data for grid points in the study area have been archived by MEDS.

The U.S. Army Corps of Engineers, also completed a 20-year hindcast for the North Atlantic, using much the same pressure data as used in the U.S. Navy hindcast, but with an improved description of storms over the east coast of the U.S.A. This hindcast used a wave prediction model developed by Resio (1981). The results of this hindcast have been archived for a number of grid points close to the U.S. and Canadian coasts.

Both of these hindcasts do not, because of their grid size, include an accurate definition of the shoreline, nor do they include allowance for any shallow water effects or consider the effect of ice in limiting wave growth. Consequently, they do not provide a reliable definition of the wave climate close to the shoreline or in the presence of ice. The above models are discussed in detail in the following sections.

Both hindcasts required considerable effort in the development and editing of the wind data. They also required very extensive data processing capabilities to undertake the analyses.

While the U.S. Navy and U.S. Army Corps of Engineers hindcasts provide coverage of the North Atlantic, they do not provide similar coverage of the Gulf of St. Lawrence. The U.S. Navy data covers the Gulf of St. Lawrence but it is considered to be unreliable because the grid poorly defines the shoreline.

Other hindcasts have been completed for locations in the Gulf of St. Lawrence and some hindcasts have been undertaken for Lancaster Sound. The major hindcasts are discussed in the following sections.

## 3.5 Hindcast Wave Data

### 3.5.1 SOWM Hindcast

The spectral offshore wave model (SOWM) was originally developed by New York University and others for the Fleet Numerical Oceanographic Center in the early seventies.

Since 1974, the SOWM model has been used to provide real-time, twice-daily analyses and 48-hour forecasts for use by the U.S. Navy in the northern hemisphere.

In response to a Seakeeping Workshop in 1975, which highlighted the lack of reliable wave data available for successful ship design, a special project was started to define the wave climate of the major oceans and seas of the northern hemisphere.

As part of this project, a twenty-year (1956-1975) deep-water wave spectral climatology has been developed and published for the North Atlantic. It is these data that are of interest to this study.

The SOWM is described in Lazanoff and Stevensen (1977), as follows:

> *"The SOWM computes two-dimensional (15 frequencies by 12 directions) wave spectra, using modified Phillips-Miles growth mechanism. Growth is limited by the Pierson-Moskowitz fully developed wave spectrum for the given wind velocity. The wave energy is spread directionally by the technique developed in the Stereo Wave Observation Program (SWOP). Wave energy is propagated across approximately 2000 grid points throughout the North Pacific and North Atlantic Oceans, on an Icosohedral-Gnomonic projection with grid spacing ranging from 160 km to 300 km.*
>
> *The Icosahedral-Gnomic projection allows great circles to be represented by straight lines within the triangles. Wave energy dissipation is a function of wind direction (wind direction 180 degrees to the wave energy direction causes the most dissipation), frequency to the fourth power, and energy in the wind sea. The model uses a three-hour time step. The SOWM does not contain any non-linear effects."*

The model does not account for wave/wave interactions. There are approximately 450 grid points in the North Atlantic.

The model takes into account the propagation of swell waves. If at the time of the calculation, the locally generated significant wave height at a particular grid point exceeds five feet, swell is propagated in a radial manner until the significant wave height of that train has decreased below three feet. The sea state at any grid point is described by the summation of the locally generated wave spectra plus the incoming swell from all directions.

The validity of any hindcast is dependent on the reliability of the wind velocity input to the model. Lazanoff and Stevenson (1977), describe the development of the wind data for the 1956-1975 northern hemisphere project as follows:

> *"First, a contract was let to a private company to produce northern hemisphere surface pressure analyses every six hours for twenty years. The surface pressure analyses were derived by using previously completed surface pressure analyses as a first guess and upgrading the analyses with surface pressure and wind velocity observations from the U.S. National Climate Center land and ship data file. The wind velocity data was used to calculate surface pressure gradients. When original surface pressure analyses were not available, the observations were used to produce new surface pressure analyses. The new surface pressure analyses were computed forward in time and were compared to the original surface pressure analyses which were computed backward in time.*
>
> *An algorithm was developed which computes modified gradient wind velocities, and accounts for air-sea temperature differences for all grid points. The winds were adjusted to an elevation of 19.5 above sea level."*

The application of SOWM to the northern hemisphere project (1956-1975), was undertaken by the Fleet Numerical Oceanographic Center.

The SOWM hindcast data set for the Atlantic Ocean has been obtained, archived and processed by MEDS to produce maps of exceedences and extreme events. These maps are presented in section 3.6. Figures 3.1 shows the position of SOWM hindcast points in the study area.

The validity and accuracy of the SOWM model has been discussed by many researchers. It is important that the input wind data, the prediction procedure and the physics be assessed.

A problem with the verification of the SOWM 1956-1975 project for the North Atlantic, is the lack of reliable and long-term wave data measured at offshore locations close to SOWM grid points. In fact, no data that meet these specifications were recorded during 1956-1975 and, consequently, any attempt at verification will be inconclusive.

A number of technical papers discuss the verification of the SOWM 1956-1975 project; Lazanoff and Stevenson (1977); Chen et al. (1979); Cummins and Bales (1980); Bales et al. (1980); and Pierson (1982), for example. None of these papers provides systematic and consistent comparison of all available data with the SOWM data. In a discussion of Cummins and Bales (1980), the need for further validation is stressed. However, it is doubtful whether firm conclusions with regard to the reliability of the SOWM 1956-1975 project are possible because of the limited data available for this purpose.

It is important to note that the major investigators, who are affiliated with the U.S. Navy, The American Bureau of Shipping, Hoffman Maritime Consultants Inc. and New York University, without exception enthusiastically endorsed the SOWM 1956-1975 data when discussing the application of these data to ship design and evaluation.

A brief summary of some of the reports describing validation of the SOWM 1956-1975 data for the North Atlantic follow.

Lazanoff et al., 1977

Lazanoff et al. (1977), in an initial assessment of the 1956-1975 hindcast, noted that the SOWM wind speeds were significantly less than the measured wind speeds in high wind conditions. However, the comparison between SOWM wave height and recorded wave height was much better than the wind speed comparison. The authors stated that, it was likely that there was an error in a wind algorithm and noted that the error would be corrected and the wave climatology would be redone. It is understood (personal communication from Lazanoff) that the wave climatology was not re-hindcast with modified wind data.

Chen et al., 1979

Chen et al. (1979), make comparisons between the SOWM data and ship-borne waverider data from Weather Station India in the North Atlantic, Weather Station Papa in the North Pacific, and with the staff gauge measurements at Argus Island. Encouraging conclusions were reached as a result of investigating trends in relationships between wind velocity and wave conditions, producing statistical distributions of wind velocity, significant wave height and average period and by making directional comparisons between measurements and SOWM estimates. Chen et al., 1979, conclude that, "*On the whole, the extensive statistical analysis and the comparison between the measured and hindcast spectral data seem to indicate favourably the accuracy of the SOWM not only in terms of hindcasting the long-term distributions of important spectral parameters such as H(1/3) and T(z), but also in obtaining the general spectral shape for marine structure response calculations*".

Bales et al., 1980

Bales et al. (1980), present comparisons between Weather Station India recorded data at the closest SOWM grid point (128) and the results of a comparison of SOWM and SEASAT wave heights. The conclusions reached by Bales et al. (1980), are as follows:

1. While the hindcast value and an estimate based upon measurements are strongly correlated, the hindcast has a random error with a standard deviation of about 1.4 m over the entire range.

2. For values of less than 1 m, the hindcast tends to underestimate the significant wave heights, but is still subject to about the same standard deviation.

3. The hindcast values do not exhibit any statistical bias with respect to "measured" values, except possibly in the low wave height region.

Cummins and Bales (1980)

Cummins and Bales (1980), note that one of the most serious failings of SOWM is that the detailed structure of a storm may be lost because of the relatively coarse spatial grid. Intense local storms may, for example, be so limited in areas as to be completely missed in the hindcasts. It is likely that for larger storms, the intensity of the storm and the resulting waves will be underestimated as the effect of a coarse grid will underestimate pressure gradients.

Cummins and Bales, 1980, conclude that *"It can be said that the wind and wave parameters (e.g. wind speed, wind direction, and significant wave height) agree well with measurements taken from ships at sea, although they may be slightly displaced in time and space. For purposes of developing a statistical data base, however, this is not considered a problem because what is missed at one grid point, is picked up at another"*.

Pierson and Salfi, 1979

Pierson and Salfi (1979), compared SOWM predictions with altimeter measurements from the GEOS 3 satellite. They found the SOWM hindcast to be generally lower than the altimeter measurements and that large differences were due to poor wind field specifications used for the SOWM.

Pierson, 1982

Pierson (1982), evaluated the accuracy of the SOWM model using measurements from spacecraft radar altimeters. Pierson concludes that *"With care in interpretation, a SOWM wave climatology, which is in preparation (the 1956-1975 SOWM project) should prove to be more accurate than those based on conventional ship reports"*.

In conclusion, it is probable that the SOWM 1956-1975 data for the North Atlantic have, provided a more reliable and complete description of the sea-state throughout the open ocean portions of the North Atlantic than previously available from other data bases. However, it cannot be stated that these data provide an accurate description of the sea-state. The fact that there are many discussions in the technical literature, concerning future changes to the procedures for estimating the wind fields and changes to the hindcast model, demonstrates that improvements could be made to these data. However, it is unlikely that the reliability of the existing SOWM 1956-1975 data will ever be quantified because of the limited recorded data available for verification. The reliability of the SOWM data produced from the operational forecasts can be expected to be less than the SOWM data from the 1956-1975 hindcast because of the lower quality of the wind data.

With regard to the study area a number of specific comments concerning the SOWM data can be made:

- The actual shoreline is poorly defined by the SOWM grid. The grid is in places in the order of one hundred kilometres west of the shoreline. A review of some severe storms shows that winds frequently blow from the west (away from the shoreline) and in reality are limited by the fetch or distance from the shoreline. These storms are without doubt significantly overestimated by the SOWM data.

- SOWM data in the northern part of the area are questionable during the winter (January to May) because the presence of ice was not considered in the model.

- In the central part of the area around Hibernia the data may be invalid during March and April because of ice.

- SOWM does not consider the effects of bathymetry or currents or the wave data. This question is discussed further in section 5.1 and is particularly important at the Scotian Shelf.

- In general it is concluded that the SOWM data provide a poor definition of the wave climate of the study area. It should be noted that these comments apply for the study area and do not apply to the open ocean.

### 3.5.2 WIS Hindcast

In 1976, a study to produce a wave climate for U.S. coastal waters was initiated at the U.S. Army Engineers Waterways Experiment Station (WES).

This Wave Information Study (WIS) involved a numerical hindcast of deepwater wave data for the North Atlantic from historical surface pressure and wind data. Development of the hindcast procedure, input data files and data presentation format, is described in a series of reports (Corson et al, 1981 and Corson and Resio, 1981). The objective of the WIS study was to provide a coastal wave climate and consequently data at all grid points throughout the North Atlantic have not been archived. Development of the historical wind field data from several pressure data sources is described in Corson et al (1981). The development of the hindcasting procedure involving wave energy propagation, dissipation and generation is described in Corson et al (1981). The hindcast produces a directional wave spectral climatology at three or six-hour intervals on a grided system. At present, 20 years of wave data have been hindcast for grid locations along the U.S. Coastline and east coast of Canada.

The WIS study covers the same period of time (1956-1975) as the SOWM study. It appears that the WIS hindcast benefited from some of the possible limitations of the SOWM study and, consequently, has the following features:

- Considerable effort was put into defining the overwater wind field particularly close to the shoreline of the United States.

- A finer grid than that used in the SOWM model was used to define wind fields during storms.

- The hindcast model contains allowance for some phenomena, such as wave-wave interaction that are not included in the SOWM model.

MEDS has acquired the WIS data for the 14 grid points in the vicinity of the study area. The data have been archived and processed to produce maps of exceedences and extreme events. These maps are presented in section 3.6. Figures 3.1 shows the WIS hindcast points in the study area.

Verification of the WIS hindcast has being undertaken. Preliminary results of the hindcast verification are provided in Corson and Resio (1981) and Resio (1982). Based on a comparison of available recorded and hindcast wave data for the Grand Banks and Scotian shelf areas, Baird and Readshaw (1981) concluded that the WIS hindcast data may not provide an adequate description of the wave climate in these areas. Some of the identified limitations included poor definition of some storms and an inaccurate description of the shoreline by the grid. However the limited availability of recorded data did not permit firm conclusions to be drawn.

Resio (1982) also assessed the validity of the WIS hindcast wave data in the Scotian shelf, Grand Banks and Labrador Sea and concluded that problems with the hindcasts of severe storms could be encountered due to the pressure grid specifications for the area. He also included that the WIS hindcast was a good first approximate but that the 20 to 30 largest storms should be rehindcast for design wave calculations.

It cannot be concluded unequivocably at this time whether or not the WIS data provide more or less reliable information than the SOWM data. However the WIS model has the advantage of having been developed after the SOWM model and may have benefited from the additional knowledge available. It is also likely that the WIS study was undertaken with significantly improved wind data than was used for the SOWM study. The shoreline is not well described by the WIS grid, but the WIS grid provided a better fit than does the SOWM grid.

In summary and with regard to the study area a number of specific comments concerning the WIS data can be made.

- The data is probably more reliable than the SOWM data.

- The WIS data may overestimate or underestimate the magnitude of some storms because of incorrect definition of the shoreline.

- The WIS procedure did not consider ice and therefore may be unreliable in northern areas from January to May and in central areas in March and April.

- The WIS procedure did not consider bathymetry or current effects. (see discussion in 5.1).

- In general it is concluded that the WIS data provide reasonable description of southernly areas where bathymetry does not have an effect. However the data are not sufficiently reliable for the estimation of extreme events (100 yr storm etc.)

### 3.5.3 MEDS Hindcasting System

The MEDS hindcasting system was undertaken following review of the WIS hindcast. It uses the identical methodology as in the WIS but includes an improved description of the wind field and has a grid designed to provide a better fit to the Canadian shoreline.

This MEDS hindcast is in a development stage and has the objective of providing MEDS with a reliable hindcasting capability to evaluate other

hindcasts. This capability can also be used to hindcast the most severe storms in an area to arrive at an estimate of the design wave height.

There are no plans this time to use the hindcast capability to produce another 20 or 30 year data set over large portions of the east coast. Such a project would be well beyond the resources of MEDS.

It should be noted that this is also a deepwater hindcast model and that suitable techniques to bring deep water waves into shallow water are only in the early developmental stage in MEDS. The model does not at present consider ice or currents.

For the limited comparisons to measurements which have been made to date the MEDS hindcast model has performed well on estimating the wave height. The wave periods have not been determined to be reliable.

### 3.5.4 Oceanwater Inc. Hindcast for Mobil Canada Ltd.

This study had the objective of determining the extreme wave conditions required for design of structures for the Hibernia area, Oceanweather (1982).

The wind field describing twenty of the most severe storms occuring during the period 1950 to 1980 were defined using archived weather maps and ship observations. The wave hindcast model driven by this wind data was based on a model developed for the Ocean Data Gathering Project, Cardone et al (1976).

The study was undertaken because Mobil considered that the data previously used by them (from the U.S. Corps of Engineers WIS) had a number of limitations. The improvements in the Oceanweather Inc. study, compared to the WIS study were as follows:

- smaller grid. The grid was approximately 150 km compared to 180 km in the WIS.

- selection of storms from a longer time period. The time period was 30 years compared to 20 years in the WIS.

- improved input wind data.

The Oceanweather Inc. study was verified by comparing the results of the hindcast for two storms during which recorded wave data had been obtained. Oceanweather (1982) reports that in one storm the model predicted a significant wave height of 11.3 m , compared to a measured value of 10.1 m. In the second storm the model predicted 8.9 m compared to a recorded value of 8.7 m.

The following summary of the Oceanweather Inc. study is extracted from Oceanweather (1982).

*"A new description of the extreme wave climate in the resource exploration area east of Newfoundland (Hibernia) is derived through the application of hindcast techniques.*

*The study began with the assembly of a comprehensive array of historical data including: archived synoptic weather maps and enhanced ship data collections covering the period 1899-1980; monthly sea-ice concentration data commencing in 1953; results of recently completed U.S. government sponsored hindcast studies covering the period 1956-1975; Canadian government wave analyses covering the period 1970-1979; published climatological summaries and studies.*

*Extreme wave events were found to be associated with the extra-tropical cyclones which, in general, formed near the U.S. East Coast, underwent rapid intensification while they moved north-eastward and passed within about 300 km of Hibernia with forward velocities less than the climatological average of cyclones in the area. The most extreme storms tended to pass to the west of Hibernia, deepen explosively (central pressure fall of more than 24 mb/day) and decelerate. Because of the proximity of Hibernia to the preferred area of maximum deepening rate and the relatively small spatial scale of such storms, reliable indentification of top ranked storms and specification of surface wind fields required ship report coverage available only within the past 30 years. Thus while a list of severe historical storms over the 50-year period 1930-1980 was prepared, the 20 storms hindcast were selected from a reduced storm population covering the period 1951-1980.*

*The file of historical surface ship data acquired in this study was found to provide more than twice the data density achievable in real time. Detailed post-analysis techniques were applied to each storm to provide surface wind field descriptions of considerably greater accuracy than may be derived from archived surface weather maps alone. It is estimated that errors of about* $\pm 2$ *m/sec in speed and* $\pm 20$ *in direction have been achieved in this study and that windspeed errors in areas of strong wave generation are unbiased.*

*A calibrated spectral wave specification model, which has been shown in previous studies to provide hindcasts of high accuracy in tropical and extra-tropical cyclones, was adapted to the Atlantic Ocean on a grid of 81 n.mi. spacing at the latitude of Hibernia. That spatial resolution allowed much more accurate representation of fetch restrictions by coasts and sea-ice than was possible in previous studies.*

*A comparison of hindcasts and measurements at Hibernia in two of the 20 storms hindcast showed model predictions of peak storm sea states to be accurate to within 1m in* $H_{1/3}$ *and 1 sec in spectral peak period,* $T_p$. *Those errors probably characterized the hindcast wave series of* $H_{1/3}$ *and* $T_p$ *generated in this study.*

*An extremal analysis of the hindcast wave series at seven grid points revealed the presence of a large spatial gradient in the extreme wave climate east of Newfoundland. The most appropriate value for the 100 year return period maximum wave height near Hibernia was found to be 30 meters, with an associated period of about 16 seconds."*

The authors are unaware of any independent assessment of this hindcast by other workers. The data remain confidential to Mobil Oil, and while they have very kindly been made available to this study, they are not as yet in the public domain.

The authors have conducted a limited assessment of the dataset with the following results.

- This would appear to be the best hindcast done to date. It is unfortunate that it covers only one small part of the study area.
- This hindcast has major advantages in that it includes the ice edge and has a finer grid defined to provide a good representation of the shoreline.
- Based on the two storms for which measured data were available the model provided reliable estimates of wave height and period.
- Unfortunately other storms for which measurements were available were not hindcast to provide further verification of the model.
- There is a substantial question, however, about the storm selection procedures. Some storms used appear to be less severe than the one year storm. Since 20 storms were selected over a 30 year period one must question whether the most severe storms were used.
- Also the study used storms for which the wave growth was fetch limited by the coast of Newfoundland and presumably, although we did not examine such a case, by the ice edge. The propriety of using such a mixed storm population in extreme value analysis is questionable.

### 3.5.5 Group Five Hindcast for Total Eastcan

This study was undertaken in 1978 for Total Eastcan Exploration Ltd., then operator for the Labrador Group, by Group Five Consulting (1978). In this study extreme statics for four locations in the Labrador Sea are presented. These data were hindcast with a parametric model using boundary layer wind velocities determined from isobars contained on synoptic weather maps. The maps used covered all severe storms that occurred between July 1 and December 31 during the years 1970 to 1976.

The four locations for which extreme wave statistics were determined are shown in Figure 3.1.

Comparisons were made between the hindcast data and the three major storms that had been recorded in the Labrador Sea (October 1973, October 1976 and October 1977). These comparisons may described as excellent, fair and poor. A major limitation of this study is the small sample of seven years from which extreme events were estimated. The event with a return period of one hundred years cannot be reliably estimated from this sample. Unfortunately, the problem of very limited reliable meteorlogical and ice cover data suitable for wave hindcasts will exist with any study of the norther part of the study area. However, a study completed in 1984 could work with twice the data that were available in 1976.

### 3.5.6 Public Works Canada Hindcast

A wind-wave hindcast was undertaken by Public Works Canada, Baird (1978), to define the wave climate at four locations in the Gulf of St. Lawrence.

Sixteen years of hourly values of significant wave height and peak period were hindcast using a parametric model and wind data recorded at Grindstone Island. The study was undertaken for the Transportation Development Centre as part of the Gulf Corridor Study, Baird (1978).

The location for which wave statistics were determined are shown in Figure 3.1.

A more accurate hindcast of the Gulf of Saint Lawrence could undoubtably be completed if more complete descriptions of the wind fields were developed. The available data may be suitable for preliminary assessments of operations close to the location for which the data were hindcast. The data are now only available in the form of scatter diagrams and have very limited use for the estimation of extremes.

## 3.6 Comparison of the Existing Data

The existing datasets providing coverage of the study area are assessed in section 3.5. In this section various presentations of these data are provided to allow comparison of the data.

The presentations include the following information, where the available data permits:

1. Estimate of the maximum value of the significant wave height with a return period of 100 years. Figure 3.9.

2. Estimate of the maximum value of the significant wave height with a return period of 20 years. Figure 3.10.

3. Value of the significant wave height that is exceeded for 10 per cent of the time during the year. Figure 3.11.

4. Value of the significant wave height that is exceeded for 50 per cent of the time during the year. Figure 3.12.

5. Value of the significant wave height that is exceeded for 90 per cent of the time during the year. Figure 3.13.

The following comments are pertinent to these figures.

### Extreme Value Analyses

The estimates shown in Figure 3.9 and 3.10 were calculated as follows:

SOWM

Fisher-Tippet Type I distribution. Data used were annual maximum significant wave heights (1956-75).

WIS

Fisher-Tippet Type I distribution. Data used were annual maximum significant wave heights (1956-75).

METOC

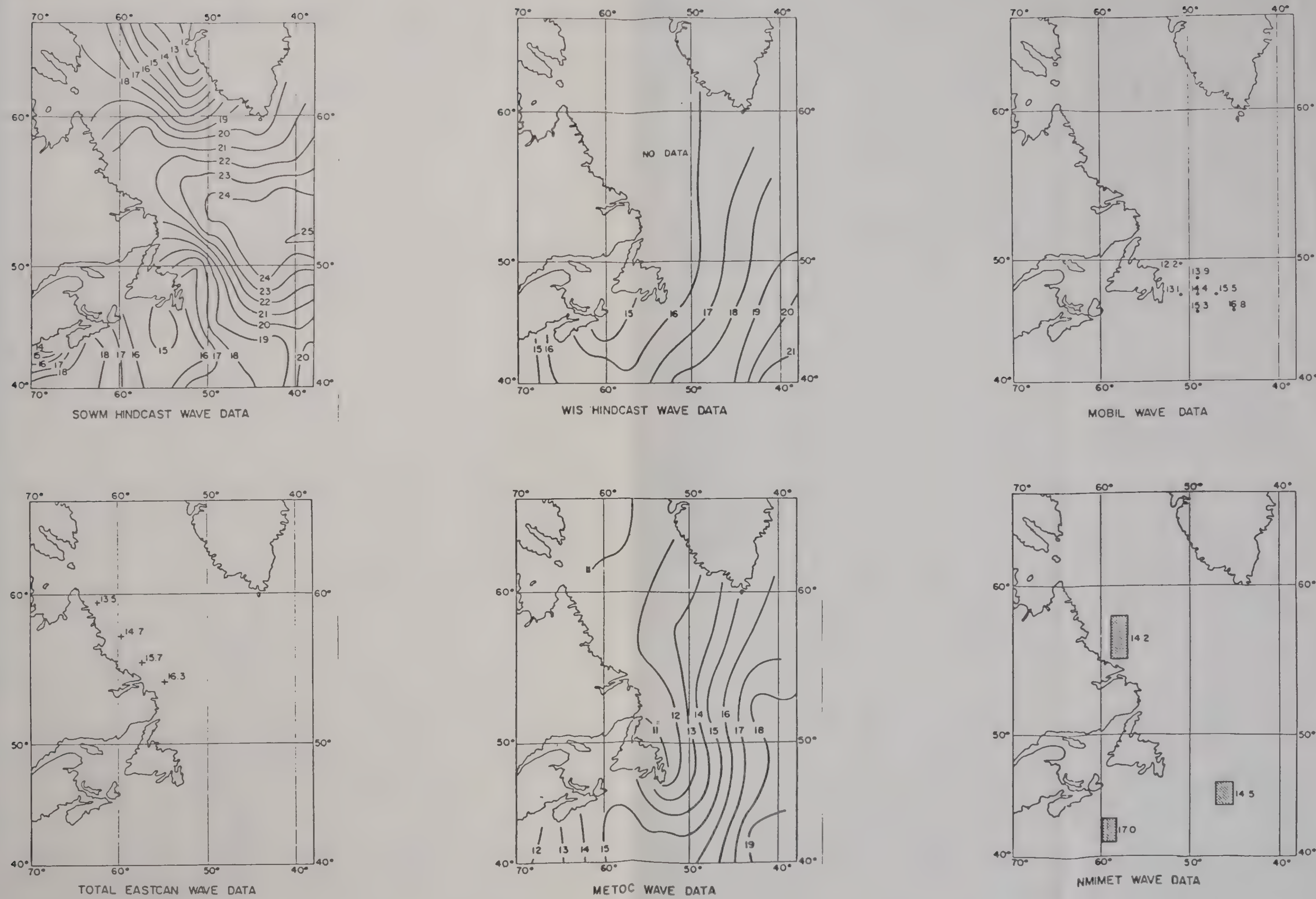
Fisher-Tippet Type I distribution. Data used were annual maximum significant wave heights (1970-80).

MOBIL

Fisher-Tippet Type I distribution. Data are used were significant wave heights from 18 storms hindcast to occur in the period 1950 to 1980.

TOTAL EASTCAN

Fisher-Tippet Type I distribution. Data used were maximum significant wave heights from more than 80 storms hindcast to occur in the period 1970 to 76.

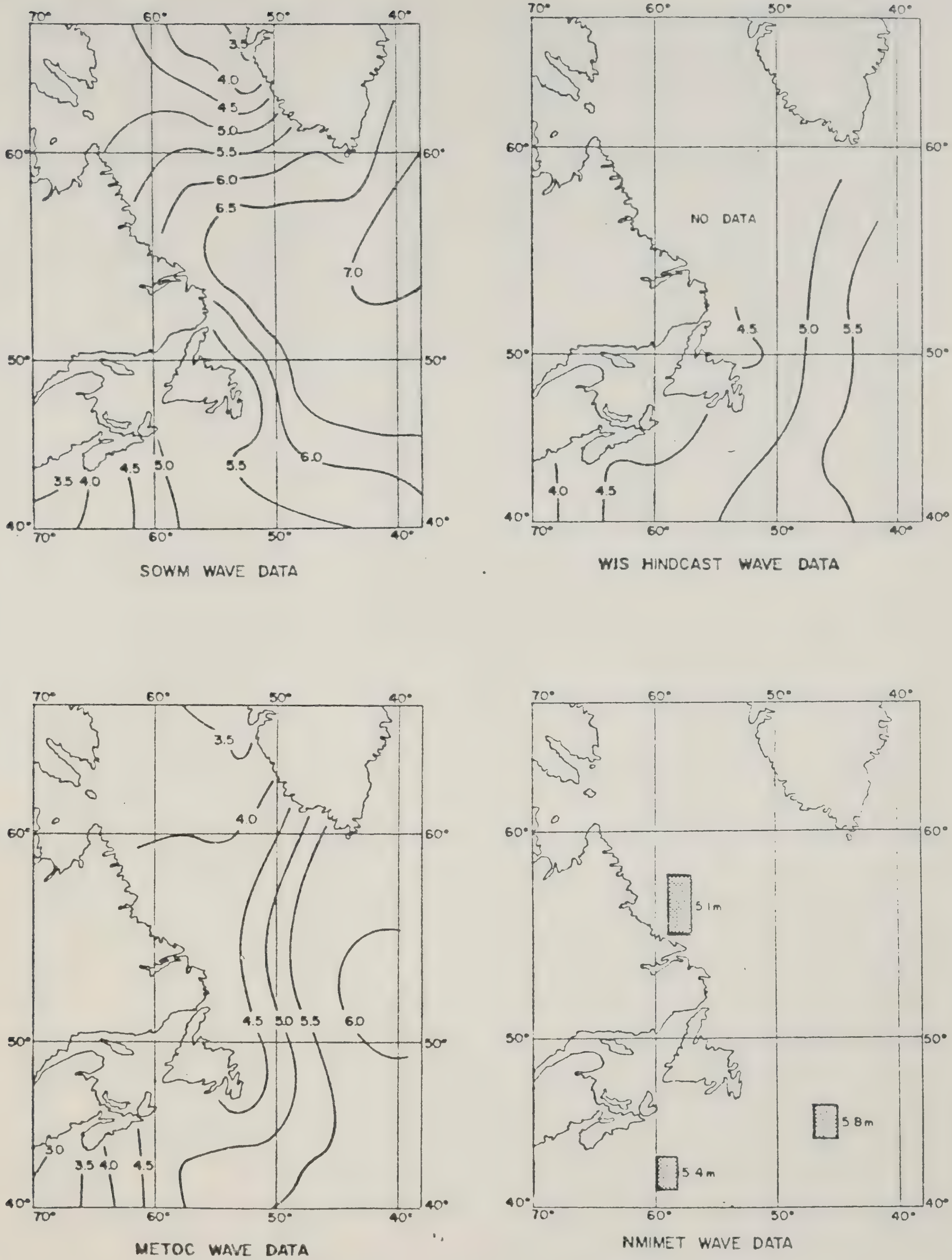



SIGNIFICANT WAVE HEIGHT (M) WITH A RETURN PERIOD OF 100 YEARS

Figure 3.9 Estimate of the maximum value of the significant wave height with a return period of 100 years.

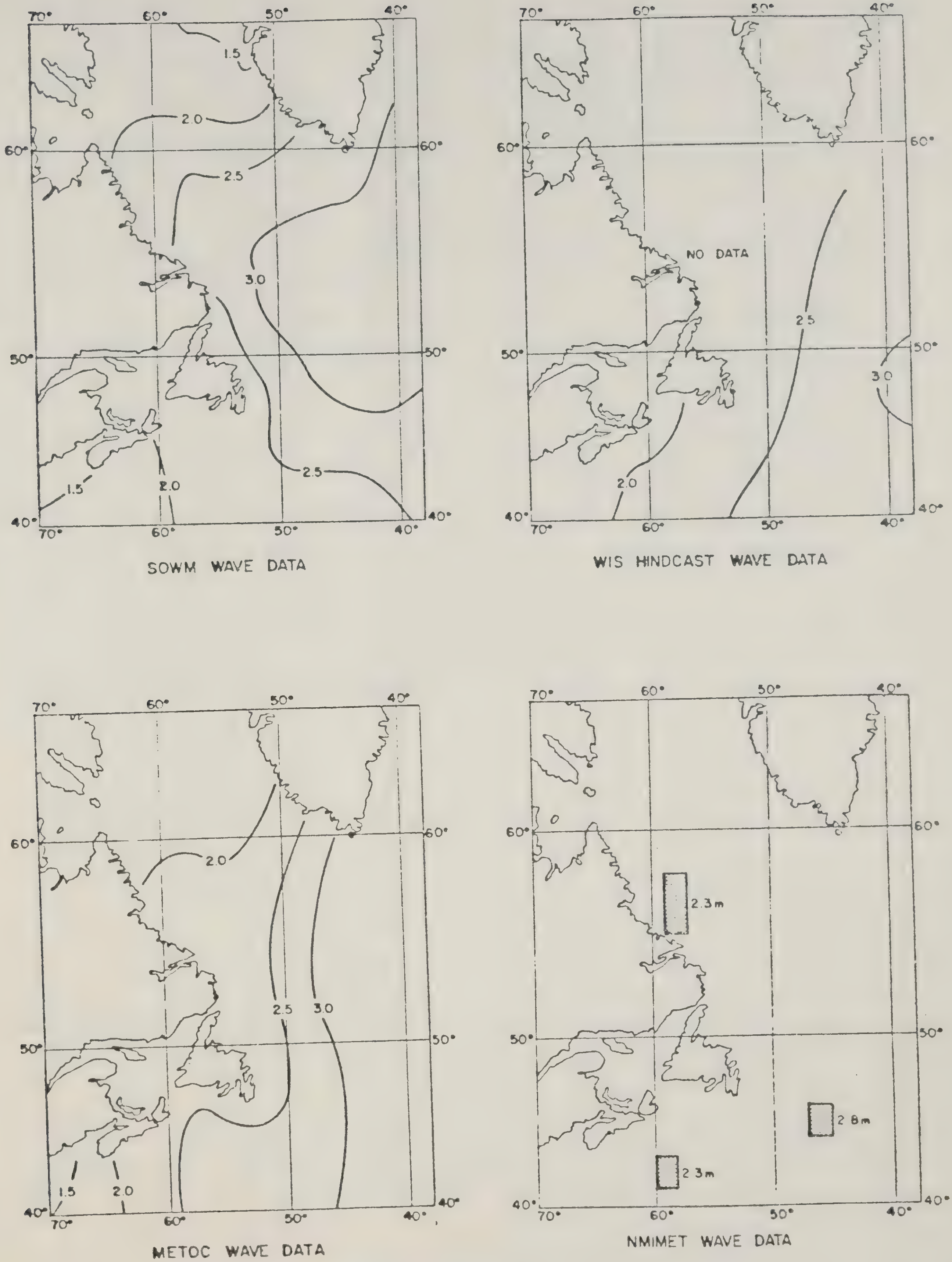

SIGNIFICANT WAVE HEIGHT (M) WITH A RETURN PERIOD OF 20 YEARS

Figure 3.10 Estimate of the maximum value of the significant wave height with a return period of 20 years.



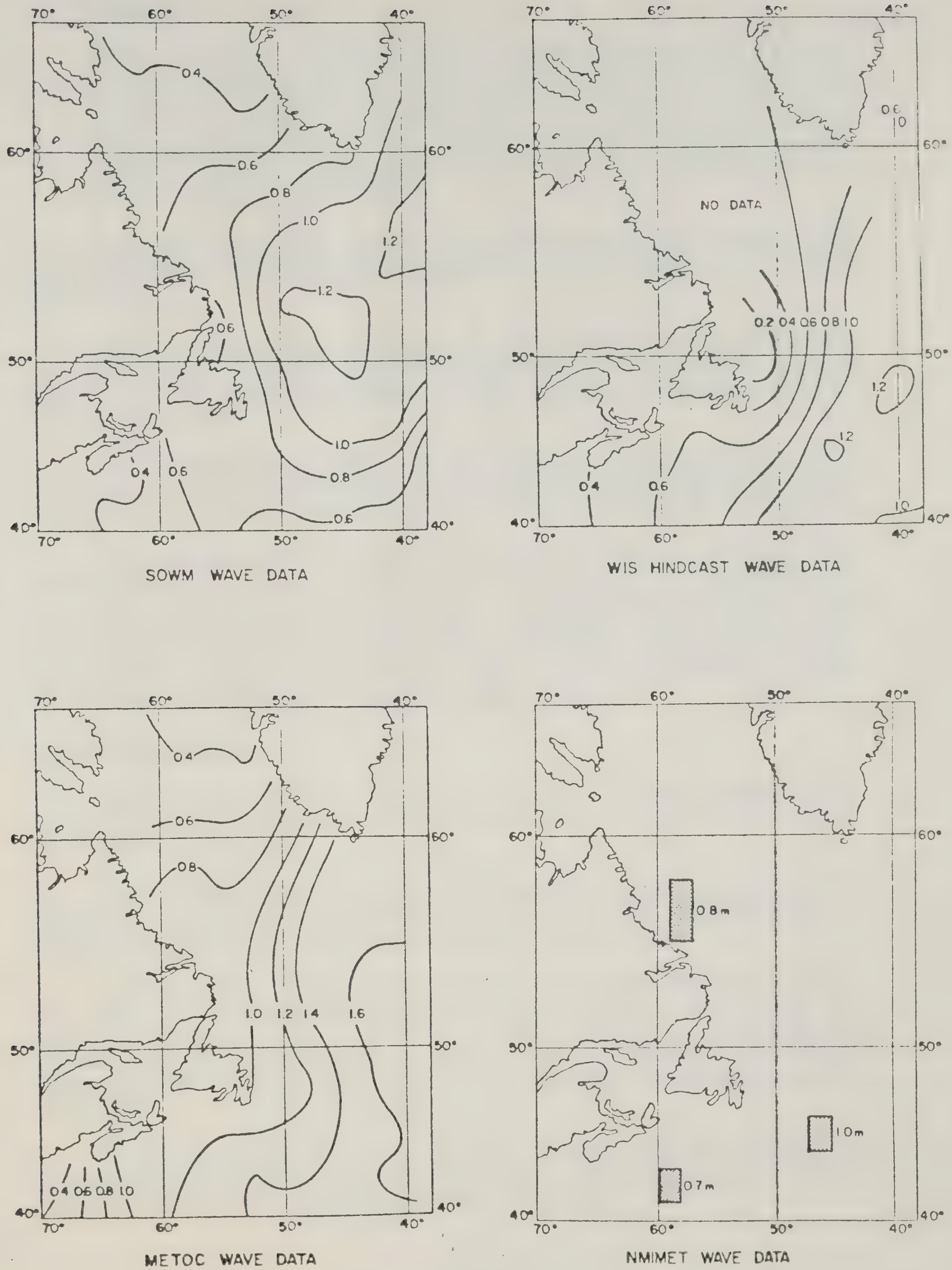

SIGNIFICANT WAVE HEIGHT EXCEEDED FOR
10 PER CENT OF THE YEAR

Figure 3.11 Value of the significant wave height that is exceeded for 10 per cent of the time during the year.




SIGNIFICANT WAVE HEIGHT EXCEEDED FOR
50 PER CENT OF THE YEAR

Figure 3.12 Value of the significant wave height that is exceeded for 50 per cent of the time during the year.




SIGNIFICANT WAVE HEIGHT EXCEEDED FOR
90 PER CENT OF THE YEAR

Figure 3.13 Value of the significant wave height that is exceeded for 90 per cent of the time during the year.

NMIMET

Weibull Distribution of all observations made in the period 1949 to 1981 (southerly locations) or 1957 to 1981 (north locations) with 20 year return period event assumed to have a probability of occurrence of $3.43 \times 10^{-5}$ and 100 year return period event assumed to have a probability of occurrence of $6.87 \times 10^{-6}$. There were 293 observations available for the northern location, 4957 observations near Hibernia and 2346 observations for the location near Sable Island.

The figures show an estimate of the extreme events and do not provide any information on the expected reliability, error or confidence in these estimates.

The objectives of these figures are to demonstrate the large variation in the extreme wave conditions that occurs throughout the study area (that is shown by all the datasets), and also the large variation in estimates between some of the datasets.

These presentations should not be used for design purposes. It is concluded that all of the datasets, with the possible exception of the Mobil data, are inaccurate and insufficiently reliable for the estimation of extremes.

As is discussed in the following section, any accepted data set should be extrapolated using a number of different procedures and careful considerations given to the confidence in any one estimate. Even with the Mobil data using the Fisher-Tippet Type I extreme value distribution, Oceanweather (1982) conclude that in 90 per cent of extrapolations the true value of the 100 year return period significant wave height would lie within approximately 16 per cent of the presented value, i.e. approximately $\pm$ 2.4 m.

Wave Climate Statistics

The estimates shown in Figure 3.11, 3.12 and 3.13 were prepared from tables showing the percentage of all records that exceed selected values of significant wave heights.

These figures also show the variation in the wave climate throughout the study area. However, the variation between the results obtained with the different datasets is not as dramatic as it is for the extreme values.

For the purpose of analysing operations considerable additional information, such as persistance statistics, average durations of storms and fair weather, may be required. In addition, it may be particularly important that corresponding data describing winds, currents and other meteorological conditions be available and be analysed with the wave data for the prediction of downtime.

It may be argued that wave data by themselves do not satisfy the requirement for design. The value of the data is very significantly increased if corresponding wind and current data are also available.

## 3.7 Discussion of Extreme Value Analysis

The problem of extrapolating time series of a given parameter to estimate the largest value that parameter is likely to take in a given period of time is a major theoretical and practical problem. There are in general use today, two types of procedures. The first type fits a statistical distribution function to all observed values in the time series. In the case of wave height the log-normal or Weibull distributions are the most frequently used.

The second type of analysis is concerned with the statistics of extreme events in the time series. In this case the observed large values (in the case of waves the large values would be storm wave heights) are selected and, typically, fitted to a Fisher-Tippett type I, II or III distribution.

In the first case it cannot be shown theoretically that the data should fit the distribution. Instead it is observed empirically to fit reasonably well over a limited range. The second technique using the statistics of extremes has a somewhat more solid basis in mathematical theory. If it can be assumed that the storms are drawn from a stationary, single population and are independent in the statistical sense; then the extremes should be distributed according to parameters which may be evaluated from the observed population.

Most of the latest work on extreme value determination is based on the second approach.

In the proceeding section an analysis of several datasets is presented to intercompare the predicted extremes. This second technique was used in its simplest form. That is, the Fisher-Tippet type I distribution was used on the observed annual maximum wave height from each dataset. This is not to be considered an endorsement of this procedure. It was used for demonstration purposes only to show the differences between extreme values from different datasets. In fact the authors believe more recent procedures using the largest wave heights from all severe storms regardless of year of occurence to be more appropriate.

The underlying objective of the use of extreme value distributions is to develop a description of the total population of all storms and then reliably estimate the magnitude of the one storm which should occur at a specific interval of time e.g. once every 100 years. This concept of a return period is purely a statistical one and it should be realized that the event may not occur in the lifetime of a generation; it may also occur several times.

This discussion is concerned with fitting an extreme value distribution to recorded, hindcast or ship observation data and then extrapolating the distribution to determine extreme waves for a given return period. This is the basis of most procedures used by the oil and gas industry to determine extreme wave conditions. Typically, this procedure is initiated with a small sample of storms from some underlying population of all storms. The sample consists of those storms which have actually occurred over the period of recording, hindcast, or observations and which have been selected using a procedure considered to be appropriate (there are many procedures).

Figure 3.9 and 3.10 described in section 3.6 present estimates of extreme wave conditions (return periods of 20 and 100 years) throughout the study area that are based on six different sources of data. There is considerable

difference between these results, because of the difference in the data. Considerable differences between estimates of extreme values may also occur depending on the methodology followed to produce the estimate. The objective of the following discussion is to review the following:

i) The estimate of the extreme event depends on the data that is selected for fit to the extreme value distribution (i.e. on the procedure used to select the data).

ii) The estimate of the extreme event depends on the extreme value distribution selected to extrapolate the data.

iii) The estimate of the extreme event also depends on the method of fitting the distribution selected to the data and on the procedure used to estimate the frequency of occurrence (or plotting position) of the known events.

iv) There is considerable uncertainty in the prediction of events with long return period. Predictions should provide an estimate of the expected reliability of the extreme event by expressing a range of values in which the event is expected to lie.

### Selection of Data

The data used for the extreme value analysis undertaken and shown in Figures 3.9 and 3.10 were the annual maximum significant wave heights.

This is a fairly common procedure that has its origins with the prediction of spring floods where it is generally true that only one event occurs each year. Clearly this is not the case with storms, several severe storms may occur in a single season, and it is possible that the second most severe storm in a year, which is ignored in this analysis, would be more severe than the largest in another year.

Other methods of selecting data include the following:

i) Maximum significant wave height associated with all storms. Alternatively the significant wave heights may be selected only if they exceed a threshold level, or by month or season.

ii) Use of all data. Many organizations have fitted some distributions to all data. This procedure has no basis in wave or mathematical theory and should be used with caution.

### Extreme Value Distributions

In Figure 3.14 the annual maximum significant wave heights are fitted to six different extreme value distributions. All of these distributions have been proposed in technical papers for fitting to events occurring in nature where extreme events are to be estimated. Other distributions exist. There is no objective theoretical or practical basis by which to select one distribution over another. It is not the intent of this report to discuss these distributions. However, it is important to note that use of those extreme value distributions assumes that the population from which the data are selected is stationary, identically distributed, and independent. In addition, the number of storms in

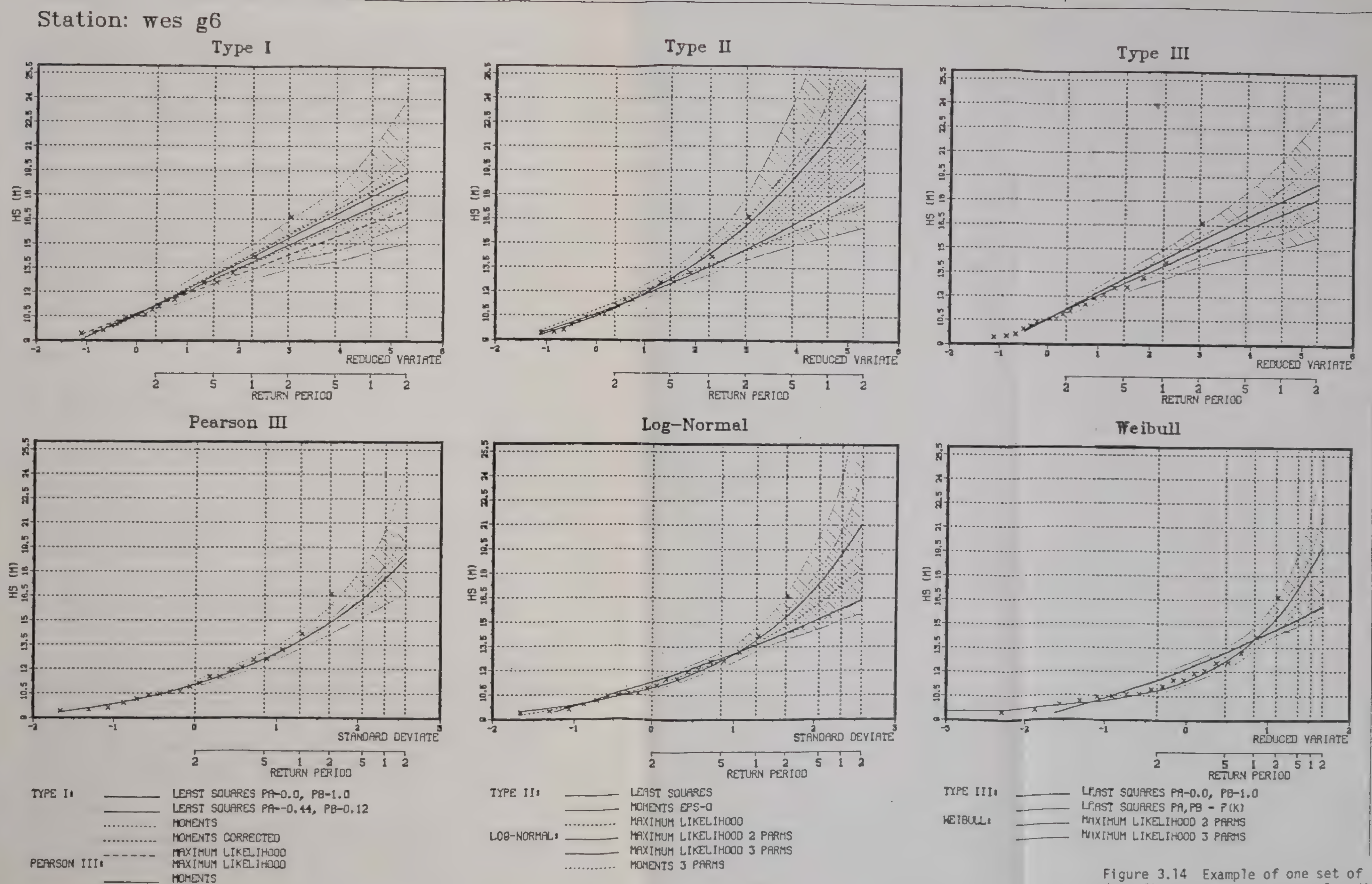



Figure 3.14 Example of one set of data fitted to six extreme value distributions. The set of data is from the WES Wave Information Study.

one sample should be large. These assumptions may be valid, but to varying degrees. In general the number of samples is small, and it is easy to realize that one could just as likely observe a significantly different sample over a time period shifted only a small amount in time. This variability in the sample will significantly affect the resulting definition of the population described by the extreme value distribution. It may also be demonstrated that the storms in the study area have different origins or are of different types and are, therefore, from different populations.

### Determination of frequency of occurrence of selected data

The frequency of occurrence, or plotting position, assigned to each wave height in the selected sequence can be calculated using a number of different methods. There is not one correct plotting position and a subjective and arbitrary choice must be made. Several plotting positions may fit the data equally well so that goodness of fit tests can not be used to select one method over another.

### Estimation of parameters for fitting a distribution to the data

The parameters of a distribution are estimated using one of the following methods:

1) linear regression
2) method of moments
3) method of maximum likelihood.

There is no consensus regarding the most appropriate method. As illustrated in Figure 3.14 the estimate of the extreme event depends on the method selected.

### Confidence limits

Once an estimate has been made it is only known to a certain level of confidence. This confidence is the combination of considerations including:

a) uncertainty in the procedure used to select the individual data points.
b) uncertainty due to the small size of the sample.
c) uncertainty due to the assumption that a particular distribution may describe the total population.

There are many methods discussed in the literature for estimating limits of confidence in estimates of extreme values. Discussion of these methods is beyond the scope of this report. However, the important point is that when the individual data points have been selected (remembering the possible error associated with each point) and one type of extreme value distribution function is assumed to fit the population then an estimate of the extreme value has a range associated with it. Typically, it may be said that in some percent (typically 90) of extrapolations the true value of the select event (e.g. 100 year return period) would lie within the range presented.

### Conclusions:

1. There is no one single method for selecting data, asymptotic distribution, plotting position, or method of fitting a distribution that has been

demonstrated to be appropriate to wave data representative of the study area.

2. An estimate of an extreme event in the study area should recognize the limitation of this estimate by providing a range of values in which it is considered reasonable that the estimate lies. This range should represent the following:

   - the possible error in the source data
   - the limitation of extrapolating from a small sample
   - the range of methods that may be used to select data
   - the different distributions that may be used to represent the parent population
   - the different methods of fitting the distributions to the data
   - the confidence in the estimate

   It is expected that this range could be several metres and <u>not less than $\pm$ 2m</u> for an estimation of the 100 year event based on <u>well verified hindcast</u> wave data selected from a 20 year period.

3. The requirement for reliable estimates of extreme waves with return periods in the order of 100 years is essential for the design of structures required for recovery of oil and gas. For structures that are undertaking exploration or delineation drilling and that are only exposed to the ocean for relatively short periods of time the requirement may be less stringent.

4. In some parts of the study area the extreme wave heights (with selected return period) will be limited by the depth of water. An example is the area around Sable Island. In these cases the extreme value analysis need only demonstrate that use of the depth limited wave conditions is not unnecessarily conservative.

## 3.8 Summary by Area

### a) Scotian Shelf Area

There are considerable data available for the Scotian Shelf as can be seen from figure 3.1. Most of the data however, are limited for reasons discussed in earlier sections. The WIS and SOWM hindcasts inaccurately described the meteorological conditions during storms and poorly defined the shoreline. Effects of bathymetry were not considered and the hindcasts are therefore suspect for most of the area. The METOC data can be considered to provide reasonable information on the wave climate for operational concerns in the deeper water areas. However there are only three METOC points on the Shelf and the data consequently do not have adequate spatial resolution.

As reliable data describing severe storms do not exist published estimates of extreme wave conditions must be treated with considerable caution, particularly in areas that are clearly influenced by shallow water or the sheltering effect of Sable Island. In some parts of the Scotian Shelf extreme wave heights are limited by water depth and additional data may not be required for the estimation of extreme conditions.

Improved estimates of extreme values throughout Scotian Shelf areas are obtainable and a start in this direction is underway. A study supported by the Environmental Studies Revolving Fund is in the process of defining the 30 to 50 most severe storms that have occurred over the area. Studies have also been undertaken, Hodgins (1984), to identify procedures for treating wave propagation in shallow water areas such as exist on the Scotian Shelf. However, the final production of extreme wave conditions throughout the Scotian Shelf area will not be achieved for several years unless a major study is initiated. In the meantime conservative assumptions must be made. It appears probable that the most urgent requirement is for a reliable description of the wave, wind and current climate of the areas where extensive activities are planned. These data, which are essential for detailed operational analysis will only be achieved through the deployment of suitable instrumentation.

Special problems to be carefully considered in any study of waves on the Scotian Shelf include shallow water effects, sheltering due to Sable Island, and possibly wave-current interactions.

### b) Grand Banks, North East Newfoundland Area

This area is probably the least complex from the point of view of developing wave climate knowledge. The area is the most uniform and the most open to waves in the study area. The water is relatively deep and the refraction and shoaling of waves may be less important here than in other locations.

There are once again considerable data available (Figure 3.1). However the SOWM data are of limited reliability for the reasons given in section 3.5.1. The WIS data may be reasonably adequate for wave climate information for operational concerns except possibly for the March - April period when ice may have been a factor. The METOC data is also considered to be adequate for operational concerns and should include ice effects. It should be noted that it may be dangerous to use average wave conditions over ice infested and

ice free years. During the ice infested years the conditions will be overpredicted. During an ice free year the conditions will be underpredicted.

There has been more work done on the prediction of extreme events on the Grand Banks and particularly in the Hibernia area than anywhere else in the study area. The Mobil hindcast, as has been stated, is the most carefully done hindcast and provides the only data that should be considered for extreme value analyses at this time. The questions on the selection of storms in this study should be addressed, and it would be desirable to undertake additional verification of the procedure before the design values are accepted. The ESRF storm identification project will assist in answering at least part of this question.

The available hindcast models can be expected to perform well for most of the Grand Banks, North-East Newfoundland area providing the wind fields can be reliably estimated and as long as the ice edge is included.

Special problems in this area include the presence of the ice edge and possibly the effects of bathymetry on extreme wave conditions. An in-depth analysis of the effects of bathymetry and currents on the extreme wave conditions is required to quantify the possible effects and determine whether or not the analyses must form a part of future studies.

c) Labrador Sea Area

There is considerably less information describing the wave climate of the Labrador Sea than for the southern parts of the study area. The limitations on the hindcast data must be considered to be more severe as one proceeds north. The ice problem in the winter - spring seasons becomes more important. The definition of the shoreline continues to be a problem. In addition one can only assume that the available meteorological data for the development of wind fields for hindcasting becomes less reliable. There are fewer and fewer weather observing stations and the presence of ships reporting overwater data becomes sparce and seasonal.

For the requirements of exploratory drilling the situation is somewhat better since this is only a summer-fall activity and does not as yet require knowledge of winter wave climate.

Because of its substantial disagreements with the other datasets in the Labrador Sea and its acknowledged problem with the definition of the shoreline, the SOWM data must be discounted as a source of wave climate information there. The WIS data was not archived for Labrador Sea points north of 53°N. The Total Eastern hindcast covered only seven years and included only the storms.

The best source of wave climate data for the area is thought to be the METOC data. These data are probably adequate for operational concerns during the summer-fall seasons when reasonable numbers of ships reports are available.

The most carefully done analysis for extreme events appears to be the Total Eastern hindcast. However, it must be used with caution and conservative assumptions should be made because only seven years of storms were treated.

It would now be possible to undertake a significantly improved hindcast with considerable more data than were available in 1976. The ESRF storm identification project should be a start in this direction.

Special problems in the Labrador Sea include accurate specification of wind fields and the effects of the ice.

d) Gulf of St. Lawrence Area

Although one would expect the Gulf of St. Lawrence to be a very familiar and well known area, this is not the case in terms of accurate wave climate information. The wave climate is clearly less severe than in the other exposed southern parts of the study area. The only hindcast available was that carried out by DPW for a specific purpose in 1978.

There are a variety of measurements made by MEDS and NRC for short periods of time. Many of the measurements, however, are in sheltered locations and could not be used to define the wave climate of the Gulf.

As stated in section 3.5.6 the DPW hindcast data could be used to provide wave climate data for operational concerns in the immediate area of the four points studied. The measured time series area generally too short to provide reliable wave climate data.

There are not satisfactory estimates of extreme waves and their return periods, for the Gulf. However there are good meteorological data from which hindcasts can be accomplished.

Special problems in the Gulf include shallow water effects, currents and ice.

e) Davis Strait, Baffin Bay, Lancaster Sound

There are no measured data and no satisfactory hindcast data for these areas. The wave climate is considered to be less severe in these northern areas then in the Labrador Sea or on the Grand Banks due to the limited fetch available in most directions for wave growth and due to the presence of ice.

The problem of developing accurate wind fields for hindcasting will be more difficult than in the Labrador Sea.

There are no available statistical descriptions of the wave climate of this area and there are no estimates of extremes.

Special problems in this area include the specifications of wind fields and the presence of ice.

## 3.9 Findings and Conclusions

This report primarily adresses the question of whether or not the data that are available throughout the study area describing wind generated waves, are suitable for the safe design and operation of structures, associated with the offshore activities of exploratory and delineation drilling.

In section 3.9.1 conclusions are drawn concerning the requirements of the industry and the availability and adequacy of the existing data.

Conclusions concerning future requirements for wave data and for studies are presented in section 3.9.2.

### 3.9.1 The Requirements for Wave Data and the Availability and Adequacy of Data in the Study Area

i) The minimum requirements of the design, certification and regulatory agencies are well defined in the available literature. Industry is, in general, satisfied that if these requirements are met, safe, efficient and effective structures can be designed and operated. The authors have found no evidence to suggest the opposite.

ii) The development of improved design procedures proceeds through several logical steps. First the research and development agency produces an advance in understanding in some area of the design procedure. This is followed by some sort of testing and a period of experience in the field. If the experience is successful then the improved procedure will gradually gain acceptance and find its way into recommended practices and procedures.

iii) The research and development organizations have a requirement for more complex and more extensive wave data for their programs which are designed to advance the state of the art and refine design procedures. These requirements are not fixed but vary with the problem being addressed by the organization and with the sophistification of its research activities. At any one point in time it is only possible to predict these needs over a short period of time into the future.

iv) There are three types of data, in general, which are required to meet the needs of the design, certification, regulatory and research organizations.

<u>Wave Climate Data:</u>

Wave climate data for the purposes of this study are considered to be statistical descriptions of the frequency of occurrence and persistance of individual wave parameters or joint distributions of two or more wave parameters. These statistical descriptions are obtained by either measuring the parameters on a regular schedule (e.g. once every three hours for five years) or by using techniques to predict what the value of the parameter might have been at every interval of the schedule.

<u>Extreme Values:</u>

Extreme values of wave parameters are the maximum value that parameter might be expected to take on in a given period of time. (e.g.

the 100 year wave height). The prediction of extreme values is accomplished in several ways but in general it requires only the knowledge of say, the history of the largest wave heights in the more severe storms in an area.

Research Data:

Research data is used here to refer to all other complex data required by research organizations in their role in advancing the state of the art in the design, certification, classification and regulation of offshore drilling units and their support units.

v) The extent of the wave data that are required by the design, regulatory and classification organizations and by the operators can be summarized as follows:

- for operational purposes - three to five years of simultaneous measurements of wave, current and wind conditions.

- for design purposes - a hindcast of wave conditions during all storms for which reliable meteorlogical data exist to adequately define the wind field. These data should cover a minimum period of twenty years if possible (in northern areas there may not be 20 years of reliable meteorological data).

vi) It has been found that the required data described above are not available throughout the study area. There are considerable differences between the various estimates of extreme wave conditions from the various hindcasts and studies. The differences between the wave climates from the various studies is not as dramatic.

It is concluded that adequate estimates of the wave climate for operational concerns exist only in some of the southern areas.

There are no values of extreme wave conditions for any part of the study area which can be accepted without further analyses.

The values produced for the Hibernia area in the Mobil hindcast appear to be the best available at the moment. However these data are confidential and have not received wide public review. There are also some questions to be resolved regarding the storm selection and extreme value procedures used. It should also be noted that the Mobil hindcast data provide only estimates of extremes and not wave climate data.

Much of the complex data required by research organizations has not or can not be acquired because of the extreme difficulty in measuring the necessary parameters or because suitable instrumentation is not available. This is a limitation to the work of many of the research and development organizations.

vii) There is little doubt that the technology and capability exists in Canada to pursue the development of the necessary data and information to meet the requirements of the organizations discussed above for wave data in most of the study area. There are two exceptions. The necessary meteorological and ice data for the extreme northern area is

probably not available. Secondly there is a requirement to develop more advanced instrumentation before the more demanding needs of the research organizations are met.

It should be noted that much of the work is of a developmental nature and for areas where the wave regime is more complex final results may not be realized for a decade.

### 3.9.2 Future Requirements for Wave Data and for Studies

viii) It is considered that wave data must be developed in the near future that will be suitable for the accurate estimation of extreme conditions in selected parts of the study area. The urgency of this requirement in the case of exploratory drilling may be somewhat less if units having unlimited class are used or if conservative assumptions are made. In the case of production facilities designed for the wave climate at the location where it is to be used, this requirement is of the highest priority.

It is also necessary to develop an improved knowledge of wave statistics that are representative of the study area.

ix) It is concluded both from the studies carried out and the interviews conducted that the development of the wave data referred to in section (viii) could best be accomplished through a joint program by all organizations requiring the data. This program would have to be fully coordinated with the programs of those organizations described in section 3.10 to maximize the usefullness of the results and gain the maximum economies in realizing the goals of all concerned.

x) It is concluded that there is a requirement to develop wave models in Canada capable of dealing with the effects of shallow water, ice and currents on waves and to verify these models experimentally in the field.

xi) It is concluded that there is a requirement to continue to develop instrumentation with increased capability to measure the directional properties of waves and their profiles. These instruments are needed to meet the requirements of the research and development organizations.

xii) It is concluded that in association with the measurement program there is a requirement for continued research into the physics of wave processes to support the research organizations with the necessary basic scientific knowledge.

xiii) It is concluded that satellite and remotely sensed data will be an important source of wave data in the future. It is important that progress in that field be monitored and that suitable actions be taken to be ready to incorporate the data into wave programs immediately it becomes advantageous to do so. However it must be noted that sources of wave data and wave climate information for design and planning of operations will not change much in the near future. The sources will be improved hindcast models based on wind fields. Remote sensing technology and advanced instrumentation will have its early effects on operations and real time forecasting. It will be some years before the knowledge of extreme events and wave climate statistics for an area

begin to benefit from the increased database. On the other hand the research and development organizations will begin to benefit immediately the data becomes available.

xiv) It is considered that programs of field measurement of waves, currents and winds are required in areas where expansion of exploratory drilling programs are anticipated. It should be noted that wave data collected with corresponding measurements or predictions of winds and currents have considerable more value to the industry than do wave measurements alone. Existing programs of simultaneous measurements of waves, currents and winds should continue in cooperation with exploratory drilling activities. These data are invaluable to later activities.

## 3.10 Organizations Obtaining and Archiving Wave Data

### (a) Ocean Science and Surveys

The Ocean Science and Surveys sector of the Department of Fisheries and Oceans has the major responsibility for oceanographic research in Canada. Major laboratories include the Bedford Institute of Oceanography at Dartmouth, Nova Scotia; the Institute of Ocean Sciences at Sidney, British Columbia; and the Quebec Region in Quebec City. In addition there are units in Ottawa with operational and research programs including the Marine Environmental Data Service and the Canadian Hydrographic Service.

There are four elements to the OSS wave program. Research into the physics of the phenomenon of waves and into wave climatology is carried out at the Bedford Institute. There is an instrument development program at the Institute of Ocean Sciences which is developing improved capabilities for the measurement of ocean waves. The Marine Environmental Data Services Branch has a large wave measurement program, does research into wave hindcasting and has developed a relatively complete computer file of wave data.

OSS is responsible for most of the wave research in government in Canada, for the provision of advice to the regulating agencies such as COGLA and Transport Canada and for the archival and distribution of its wave data holdings.

### (b) The Atmospheric Environment Service

The Atmospheric Environment Service is the agency responsible for weather forecasting and operational wave forecasting. They also collect, distribute and archive the visual observations of wave height from ships of opportunity. The other very important role of AES in the wave climate area is the provision of accurate wind fields for wave hindcasting and the contribution of scientific knowledge of winds in the development of advanced wave models.

AES also is active in the routine production of the twice daily wave charts and forecasts which go out via facsimile broadcast from the DND Meteorology and Oceanography (METOC) centres on the east and west coasts. The METOC centres are DND centres staffed primarily by AES meteorologists on secondment.

### (c) The Department of Public Works

DPW is both a customer and a provider of wave climate information. In their work in designing and building marine facilities such as harbours, breakwaters, etc., they require various types of wave information. They have therefore developed such tools as hindcasting procedures and wind and wave data presentations and formats for internal use. These developments are useful to other clients requiring wave information. The primary source of data for DPW is the MEDS measurement programs and the AES wind data banks.

### (d) National Research Council

The role of the National Research Council at the present time is related to their program in testing the performance of fixed and floating structures

through physical modeling studies. They are primarily a customer for prototype wave data but in the course of their work they develop requirements for specific wave data analyses, unconventional wave parameters and climatologies which are of broader interest.

(e) Transport Canada

Transport Canada are also primarily customers for wave data and information. However in their role as a regulatory agency they find it necessary from time to time to commission specific wave studies to provide them with information necessary for the decision making process.

(f) Department of National Defence

The DND have a requirement for real time wave information which is met through their operation of the METOC centres on the east and west coasts. Data are relayed to METOC centres from the ships of opportunity observing program and from MEDS wave buoys through either the weather observers on oil rigs or satellite communications. The METOC wave charts are a source of visual wave height, period and direction information over the past decade and a half. DND also has an oceanographic program at Royal Rhodes which adresses wave problems from time to time.

(g) Canada Centre for Inland Waters

The Canada Centre for Inland Waters has a wave program designed around its wind-wave tank facility. The facility is quite modern and sophisticated and is excellent for researching problems in the wave generation and decay processes.

(h) Universities

There are several universities in Canada with oceanographic or civil engineering programs which have wave components. Included are UBC, Dalhousie, Memorial and Queens Universities.

(i) Oil Industry

At the moment the oil industry has one of the largest requirements for offshore wave information in support of both exploratory drilling and development of production plans. The industry commissions a wide variety of wave studies using the services of a growing engineering consultant industry in order to obtain information for engineering design and in order to provide the government regulatory agencies with the information they need to evaluate the various aspects of operation.

(j) Engineering Consultant Industry

This industry in Canada has been substantially strengthened over the past few years because of offshore oil activities. It includes strong capabilities in environmental studies in the wave field.

(k) Government Funding Agencies

Government wave programs are funded in a variety of ways. The four

primary sources of funding at the moment include regular departmental A bases, the Office of Energy Research and Development, the DSS Unsolicited Proposal Fund and the Program for Industry/Laboratory Projects.

An additional funding route exists for certain classes of joint industry/government environmental studies. This is the Environmental Studies Revolving Fund.

## 4.0 Wave Data for the North Sea

Production of oil and gas has been taking place in the North Sea for many years. Therefore, it is valuable to compare the wave data produced for the design and operation of North Sea structures with that available in Canadian waters and to note the identified limitations of North Sea data so that the same limitations may not exist in future Canadian data. The following discussion is primarily based on the experience of the U.K. Institute of Oceanographic Sciences (IOS).

### 4.1 Recorded Wave Data

Wave recorders (Waverider buoys) are installed off many platforms in the North Sea. However, this is not required by regulation, a fact which is regretted by IOS scientists. In Norwegian waters the owner is required to obtain and provide wave data to the regulatory agency. In the U.K., even when data are obtained by the owner they may not be available to other organizations.

Shipborne wave recorders have been installed on some ships stationed at important locations in the North Sea. A 3 year project was initiated to obtain data at three locations in U.K. waters using this method. The project was not entirely successful because poor data recovery was experienced.

In summary, the requirement for long term recorded data is recognized and some success has been obtained. However, the extent of data available is less than is considered necessary.

### 4.2 Hindcast Wave Data

The existing U.K. guidance notes which describe the 50 year return period maximum wave height throughout U.K. waters were primarily based on a parametric hindcast using extreme winds provided by the U.K. Meterological Office (Draper 1972). More recently a spectral hindcast, named NORSWAM, was completed by U.K. Government scientists after initiation by the U.K. Petroleum Operator Association and the Department of Environment (U.K. regulatory Agency). NORSWAM hindcast 42 severe storms occurring during the period 1966 and 1976. Data from the hindcast were archived for locations throughout the North Sea. Following analysis of the NORSWAM data it was concluded (Haring 1979) that the existing Guidance notes did not underestimate extreme wave conditions.

### 4.3 Visual Observations

The same visual observations are available for North Sea Waters that are available in other areas frequented by shipping. These data were not used in preparing the U.K. Guidance Notes.

### 4.4 Extreme Wave Conditions

Estimates of extreme wave conditions for the North Sea are contained in "Guidance for the Design and Construction of Offshore Installations" prepared by the U.K. Department of Energy, the U.K. regulatory agency, and in "Rules for the design, construction and inspection of Offshore Structures; Appendix A

- Environmental Conditions" prepared by Det Norske Veritas. Similar publications have not been prepared for Canadian waters by either regulatory agencies or classification societies.

In addition, a number of technical papers discussing extreme wave statistics based on recorded data and the NORSWAM hindcast data are available, Haring (1979) for example.

## 4.5 Conclusion

A comparison of North Sea data with Canadian data leads to the following conclusions:

i) More long term measured wave data has been obtained in the North Sea than in the study area in Canada.

ii) Based on North Sea experience, efforts to obtain long term measured wave data in offshore areas of Canada are essential to the development of reliable data required for the design and operation of structures.

iii) The major hindcast study for the North Sea (NORSWAM) was initiated by industry and undertaken by Government scientists. In Canada recent studies have been completed by individual companies. One study, supported by all organizations and designed to provide the most complete and accurate information possible for all important offshore areas has not been undertaken in Canada.

iv) Guidance notes, which should provide the best estimate of extreme wave conditions available and which can form the subject for technical debate within the industry, regulatory agencies and classification societies, do not exist in Canada.


AREAS WHERE DEPTH OF WATER
IS LESS THAN 100 m.

Figure 4.1 Portions of the study area where the water depth is 100 m or less.


AREAS WHERE DEPTH OF WATER
IS LESS THAN 50 m.

Figure 4.2 Portions of the study area where the water depth is 50 m or less.

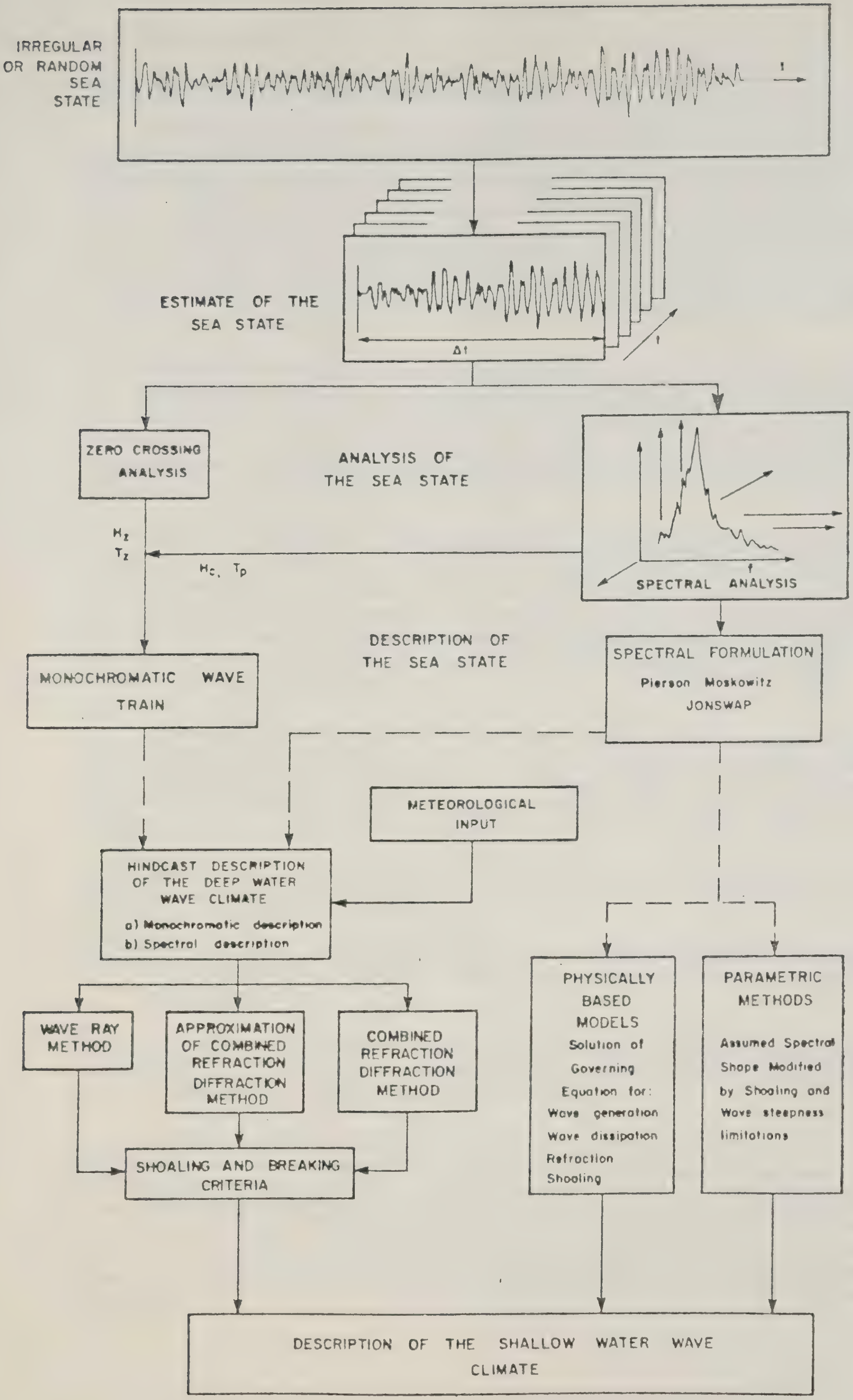



Figure 4.3 Procedures to evaluate the effects of bottom topography on wind generated waves.

## 5.0 Special Study Areas

### 5.1 The Shallow Water Transformation of Waves

As waves propagate shoreward from deep water, they begin to interact with the seabed and the wave height, wave length, wave direction and, in some circumstances, wave period, begins to change. These transformations are the result of several physical processes, some of which act in combination and some of which may act independently. The net result is that the physical characterisitics of the wave climate will be substantially different in shallow water than observed or estimated in deep water. Wave heights may be higher, or lower, then the offshore wave heights and wave breaking may occur because of the limited water depth.

In general terms, the bottom topography begins to significantly influence the propagation of waves in water depths that are in the order of one-third of the wave length or less. The shallower the water and the more irregular the ocean bottom, the greater will be the resulting changes to the waves. During severe storms wave periods may reach 15 secs and these waves will begin to be influenced by water depths of 100m.

Figure 4.1 shows the parts of the study area where the water depth is 100m or less. A study of extreme wave conditions in these areas should consider the possible influence of the bottom topography on the magnitude of the predicted events. In general, the bottom is relatively flat and dramatic changes to the wave characteristics do not appear to be likely for most areas. However, there are exceptions where the bottom topography is irregular and relatively steep slopes exist.

Figure 4.2 shows the parts of the study area where the water depth is 50m or less. In these areas attention should be given to the effects of the bottom topography when developing wave climate statistics. The influence on extreme wave conditions can be expected to be particulary significant in these areas.

Procedures for the calculation of shallow water transformation of wave data can be divided into two types:

a) procedures for the representation of a random or irregular sea-state by long crested monochromatic waves with a single frequency or period and uniform height or

b) procedures for the representation of a random sea-state using spectral methods. These spectral representations may include directional and non-directional wave spectral formulations.

A general outline of these procedures is presented in Figure 4.3. The correctness of either approach is still a matter of debate in the coastal and ocean engineering community. Procedures for a long crested monochromatic wave with a single frequency are in wide-spread use and procedures for various spectral formulations also exist. However, the majority of on going research in the area of shallow water transformation is directed to the development of generalized formulations for spectral methods to be used by the engineering community.

Procedures for long crested monochromatic waves with a single frequency can include the effects of wave refraction, wave shoaling, wave energy dissipation due to bottom friction and breaking in shallow water. No account is made for additional wave energy generation by the wind as waves propogate shorewards or for energy dissipation mechanisms such as bottom percolation or breaking induced by wave steepness instability, or for non-linear wave-wave interactions.

In general most of these procedures are either unverified or only verified in certain special or idealized applications.

Procedures for spectral formulations can be divided into two types:

a) those based on parametric models

b) those based on physically realistic formulations.

Parametric methods are based on the concept of representing the random sea-state with an assumed spectral shape defined by a limited number of parameters. Parametric models have been developed which implicitly incorporate non-linear wave interactions by the assumed shape of the spectra, but they do not incorporate transformations caused by interaction of the sea bed and the waves.

Physically based spectral formulations include terms which describe the wave generation mechanisms, such as the Philips' resonant mechanism and the Miles' stability mechanism, wave energy dissipation terms for bottom friction and wave breaking and terms to describe refraction and shoaling. The non-linear wave interactions are not included in these formulations primarily because of the extensive complications which would result in the computational solution.

Physically based spectral formulations also exist for both stationary and non-stationary meteorological conditions. Non-stationary conditions include combinations of sea and swell arriving at a shallow water location where either the offshore meteorological conditions producing swell are changing or the local meteorological conditions producing local seas are changing. Changes in the meteorological conditions can include variations in the wind strength or direction. Stationary conditions assume that no changes are taking place.

In general, parametric based models for shallow water can only describe local stationary conditions although non-stationary models in deep water have been developed and used in other areas.

It should be noted that existing physically based methods do not include non-linear wave interactions primarily for two reasons:

a) well tested models for shallow water do not presently exist or are in the research state. Models do exist for deep water conditions.

b) Including non-linear terms in existing computational schemes will result in costly and complicated procedures.

It is generally agreed among researchers that the non-linear wave interaction terms may be the most important parameter in the shallow water transformation. However, there is not total agreement and some researchers feel that the apparent importance of non-linear terms may be the by-product of existing simplistic linear models for refraction, shoaling and the lack of consideration of the effects of short crestedness and directional characteristics of the random sea-state.

In all cases, existing procedures for the shallow water transformation of wave data are either unverified, or have been verified with limited data or in special circumstances. Caution should be exercised in the application of any particular method which has not been verified against data obtained in the area of interest.

During the course of this investigation the following conclusions were drawn regarding the influence of bottom topography on wave conditions in the study area.

1. An in-depth analysis of wave transformation due to water depth was not identified for any location within the study area, following review of the available technical literature.

2. None of the wave hindcast studies summarized in this report consider the effects of bottom topography in possibly increasing or decreasing the predicted wave heights.

3. It has been postulated but not proven, that water depth may have a significant effect on the wave climate, in particular extreme wave conditions, in some of the more active parts of the study area such as Hibernia or Venture.

4. Existing methods of simulating wave transformation are limited by a general lack of prototype verification. Application of these methods to the study area may be particularly difficult (and very expensive to complete) because of the very large area that may influence the wave climate at a selected location and because of the probable need to consider simultaneous wave transformation and wave generation.

## 5.2 Non-Conventional Wave Events

A number of possible wave characteristics have been identified as having the potential to produce motion or stress responses in a structure that are significantly different from those estimated to occur using analysis procedures with standard wave characteristics. These characteristics, referred to in this report as non-conventional wave events, include non-symmetric wave geometry, breaking waves in deep water, wave grouping and 'freak' waves.

This concern with non-conventional events is being demonstrated by hydraulic laboratories that have recently developed improved capabilities in simulating realistic sea-states.

It will take time before these concerns can be represented in design procedures because the available recordings of measured waves do not provide sufficient information to document these characteristics or to allow the frequency of occurence of these characteristics to be defined.

It should be noted that while the industry is closely monitoring the progress being made in hydraulic laboratories and by scientists concerned with wave measurement, there is not a concern that existing design procedures are unsafe. There is no published prototype evidence supported by measurement, to suggest that any structure associated with the oil industry has been damaged as a direct result of one of these non-conventional wave events.

Wave characteristics that are being studied at present are as follows:

### 5.2.1 Wave Assymetry

There is evidence from wave recordings that the average slope on the leading side of a wave is steeper than the following side. The steepness on the leading side may be greater than assumed in design procedures and has the potential of producing larger loadings when the wave interacts with a structure.

### 5.2.2 Wave Breaking

Breaking of waves in deep water have been characterized, Mason (1952), as 'plunging', a situation where the wave crest curls forward over the front slope of the wave and 'spilling' where the wave crest spills down the front slope. Leblond (1982) notes that breaking is a manifestation of strong non-linearities of the free surface boundary conditions and that is one of the least understood aspects of water waves.

Wave breaking is known to result in a condition where waves move into an opposing current as well as when the non-linear interaction of several waves in a train occurs.

Field investigation of breaking waves is the subject of a possible research program to be undertaken in the North Sea by U.K. scientists.

### 5.2.3 Wave Grouping

It can be observed in many wave records that the larger waves are grouped together rather than being randomly dispersed within the wave record.

It has been demonstrated that some structures respond differently to the two wave trains (one with the larger waves grouped together) even though the average or significant wave height for the two records may be the same. The effect is due to two phenomena. A group set-down under a wave group and an associated set-up between groups leads to the formation of long waves which can excite structural response. This is important in shallower water. The successive occurrences of several large waves in a group in conjunction with the non linear response of structures to waves leads to excitation frequencies which are related to the group repetition frequency rather than the wave frequencies. This is important for large structures.

Wave grouping is presently being extensively reviewed by many researchers. It is, for example, proposed by some researchers that wave grouping occurs in any wave record providing the record is long enough and that the frequency of occurrence of wave groups is predicted by existing statistical theory. Other investigators believe the observed grouping is more frequent than can be explained by existing theory.

However, the fact that wave groups do occur requires that their effect on the stability, motions and integrity of structures be investigated.

### 5.2.4 Freak Waves

The words 'freak', 'rogue', 'episodic', 'abnormal', are used to describe very large waves that have been encountered in the oceans. There exist many reports of ships encountering and being damaged by such waves. These reports are occasionally supported by photographs.

There is at present no theoretical basis to describe these waves or their frequency of occurrence in the ocean.

Existing statistics predict the presence of large waves that may have a height in the order of two times the significant wave height. The large waves occur as individual wave crests are superimposed when different wave trains interact.

In the presence of a horizontal current gradient, refraction of waves may occur resulting in a concentration of wave energy. And an opposing current will cause waves to become steeper. Many of the ship reports of 'freak' waves have occurred in areas where strong ocean currents exist. An analysis of wave interaction with currents that may occur in the study area and the possible consequence of increased wave heights has not been published.

### 5.2.5 Three-dimensional Sea-States

Prototype sea-states have three-dimensional characteristics. Waves do travel in different directions and, except for swell waves do not have a constant height along the crest. This is easily observed and it is clear that structures will respond differently to the real sea-state compared to a situation where all the waves are assumed to travel in one direction and the height does not vary along the wave crest.

However, the fact is that there are very few measurements of directional seas. Instruments exist that are theoroetically capable of measuring the directional characteristics of prototype sea-states. However, these

instruments are only recently available and have not yet provided a substantial body of data.

### 5.2.7 Conclusion

The most serious limitation to research into non-conventional wave events, as described above, is the lack of suitable prototype measurement of waves.

In the authors' opinion one of the more important items of research to support the development of future design procedures is prototype measurement of waves.

This measurement program should have the following emphasis.

1. Point measurement of surface profile from a fixed location.

2. As complete a description as possible of directional wave characteristics.

3. Continuous recordings during storm events.

4. Mapping of the sea surface at an instant of time (as might be obtained from stereo photography).

## 5.3 Future Sources of Wave Data

There are only three sources of future wave data which show promise for the collection of additional wave data useful in the development of wave climate information off the east coast of Canada. The first area is the development of advanced instrumentation. The second is the development of aircraft and satellite remote sensing capabilities. The third is the development of land based radar sensing of waves and currents. These potential sources are described below.

### 5.3.1 Advanced Instrumentation

There are two types in site instrumentation which either have recently reached the market or are under development which are of great interest. The first is the surface based heave and tilt buoys produced by Datawell of the Netherlands and Endeco of the U.S.A.

These buoys are designed to measure wave direction as well as wave height spectra. If they can be shown to meet the manufacturers claims they will permit the collection of directional data on a routine basis. These data will be extremely useful in verifying hindcast models and will thus permit the use of the directional outputs of these models with increased confidence. In addition the more complex directional data required by the research organization will begin to become available.

The second instrument is under development at the Institute of Ocean Sciences, Department of Fisheries and Oceans, Patricia Bay. It consists of an acoustic package which sits on the bottom and senses the sea surface shape using high frequency sound waves. Theoretical calculations indicate that the device should be able to measure directional wave spectra. It is also unique in

that it will measure wave lengths and slopes directly rather than depending on theoretical considerations to convert time series to wave shapes.

### 5.3.2 Applications of Airborne or Satellite Remote Sensing to Wave Data Collection

#### Introduction

The remote sensing of ocean waves from satellite systems offers many advantages. Since all of the present techniques make use of active microwave sensors, they return data equally well during day or night and in all kinds of weather. They can provide wave information from all ocean areas surrounding Canada depending on the choice of orbit. Each of the instruments available have characteristic ground coverage ranging from kilometres to hundreds of kilometres in width for a single orbit. The satellites carrying these sensors operate in low orbit and therefore have large ground speeds which means very quick sampling of large areas along the ground track. Because of the volumes of data that may be acquired relatively quickly, it would be possible to sample wave conditions over a large area in a short time compared to the conventional point measurements currently used. The data so acquired must be incorporated routinely into the present system of analysis before it will be of use to offshore operators.

#### Instruments

There are three instruments used aboard satellites which can provide wave data. The first is an altimeter. Such an instrument can provide information on significant wave height and large scale currents. It also may have the potential for yeilding directional wave spectra, dominant wave direction and information on swell waves.

The second instrument is a scatterometer. This device is used to sample the surface wind field to provide observations of speed and direction. It was used successfully on SEASAT to provide large scale coverage of winds. In order to arrive at wave information the wind data would have to be used in conjunction with some kind of wave forecasting or hindcasting model.

The last instrument is a synthetic aperture radar (SAR). This can be used for making direct observations of the ocean waves. Processing of the high data volumes can yield directional wave spectra and information on small scale surface currents.

All of the above instruments require a substantial amount of computer processing before the wave information can be extracted. It appears that the altimeter requires the least since it will give a direct measure of average wave properties. The scatterometer data requires less work to extract the wind information than the SAR but the wind data must be used with a wave model so that it would seem that approximately the same effort is required for both instruments.

#### Historical Data

Two satellites have carried the instruments described above. The GEOS-3 satellite had on board an altimeter which was improved upon by the altimeter on board SEASAT. The first use of a SAR and scatterometer were

made with SEASAT. The SEASAT altimeter looked straight down with a swath (the swath is the width of the ocean surface illuminated by the radar and from which data are returned) of 2.4 to 12 km depending on sea-state. (Born, Dunne and Lame, 1979). It was designed to return surface height measurements accurate to 10 cm for sea-states less than 20 m. The estimated significant wave height was projected to be accurate to plus or minus 0.5 m or 10%, whichever was greater.

The scatterometer had a swath width of 500 km on each side of the ground track of the satellite. The projected spacial resolution was 50 km by 50 km. Surface winds were to be precise to plus or minus 2 m/sec and 20 degrees for winds speeds between 4 to 26 m/sec.

The SAR had a swath width of 100 km with a spacial resolution of 25 m. The radar looked off to the side and at 20 degrees from nadir. Because of high power consumption by this instrument it was only operated sporadically. Much of the data returned from the SAR have yet to be analysed 6 years after SEASAT failed.

### Potentials for Use

A summary of the capabilities of all of the these instruments is provided by Huang (1979) and Brown and Cheney (1983). The significant wave height measured with an altimeter has been demonstrated to be comparable to surface wave observations with a standard deviation of 30 cm for wave heights below 5 m, and wind speeds below 10 m/sec. These type of measurements have been shown to be superior in reliability compared to standard ship reporting. Research is preceeding to enable routine analysis to extract directional wave information, and dominant wavelengths. Altimeters are low power, low data rate instruments for which fairly standard techniques exist for analysis. They are relatively easy to build and operate on a satellite. They return only limited wave information over a relatively small swath so that long operation times will be required before the necessary statistics may be acquired to develop reliable estimates of extreme wave conditions. Because of the small swath, the use in operational wave forecasting will be primarily as a calibration tool for wave models. In this respect, the data returned from an altimeter will be only an enhanced version of spot measurements such as returned from a Waverider buoy.

A scatterometer is also a low data rate instrument with low power requirements. The areal coverage is large so that world ocean coverage is possible every day. The spacial coverage is relatively coarse but permits the resolution of the major meteorological wind fields. The data returned can have some directional ambiguity but this can be resolved with suitable data processing. Comparisons of SEASAT derived winds to surface measurements show an RMS difference of about 1 m/sec for large and medium scales.

The data returned from a scatterometer can yield estimates of wave properties through the application of a wave hindcasting model which can make use of the large scale wind anaylses. The reduction of the scatterometer data to wind velocities and grid scales appropriate to such models is not automatic but appears to be easily done. The reliability of the wave results are then a function of the model and how important the smaller scale wind variations, not well resolved by the scatterometer, are to the generation of waves.

The SAR is a high data rate, high power instrument. A typical swath width is 100 km with 25 m resolution. Preliminary estimates of the ability to image waves gives direction estimates to plus or minus 25 degrees and wavelengths to plus or minus 15%. Further work on SEASAT data is continuing and reducing these estimates. A SAR is not yet capable of returning wave height information although various authors have done comparisons between SAR and wave buoy spectra. A SAR is seen as the only way large scale observations of waves may be done. With dedicated processing facilities, wave information can be extracted in time for operational use of the data either directly or as calibration points of a wave hindcast.

### Satellite Programs

There are a number of satellites being planned to carry these instruments and all scheduled for launch about the end of the 1980s or early 1990s. Canada's RADARSAT will have on board a SAR plus other instruments to be decided upon (a scatterometer is under consideration). Part of the prelaunch work is the evaluation of the SAR as a sensor for deriving wave parameters. The United States is considering two satellites of note. One, called NROSS (Navy Remote Sensing Ocean Satellite System) will carry a scatterometer. It is due for launch around 1988. The second is part of the TOPEX experiment designed to measure the sea surface slope and thereby ocean currents. It is designated to carry an altimeter with finer operating constraints than the one aboard SEASAT. It is due to be launched sometime in the early 1990s subject to budgetary considerations. The European Space Agency is designing a satellite (ERS-1) to carry both a SAR and scatterometer. Canada is participating in the planning of this system and therefore will have direct access to the data returned from the instruments. This is due for launch about 1988. The Japanese are also planning a satellite borne SAR again to be launched in the 1990s. Finally, the French are planning the launch of an altimeter sometime in this time period as well. It is clear that by the early 1990s these sources of wave data will begin to be available from many different sources. By this time some of the potential, but as yet undemonstrated, uses of these instruments may have become routine.

### 5.3.3 Land Based Radars

The third area of development is the land based radars. Two versions exist which claim to image the sea surface and return wave data. The first version is the CODAR which is a relatively small instrument located close to the beach. It images about 60 km out to sea and is reported capable of measuring wave heights and directions as well as surface currents. The second radar is an over the horizon type one which depends on reflection from the ionosphere to image the ocean surface. An experiment has been carried out with a high power radar in Rome, New York supplying the beam and a receiver in Ottawa receiving the returned signal. A significant portion of the Labrador Sea was imaged.

Both these radars are in the development stage. It is not clear at this time if and when accurate data which can supplement wave climate data in Canada will be available.

References


1. American Bureau of Shipping, 1980. Rules for the Building and Classing of Mobile Offshore Drilling Units.

2. American Bureau of Shipping, 1983. Rules for the Building and Classing of Offshore Installations, Part I Structures.

3. American Petroleum Institute, 1982. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms. API Report RP2A, Thirteenth Edition, January 1982.

4. Andrews, K., Dacunha, N.M., and Hogben, N., Wave Climate Synthesis, National Maritime Institute, NMIR149, January, 1983.

5. Ashe, G.W.T., and Ploeg J., 1971. Wave Climate Study Great Lakes and Gulf of St. Lawrence, Volume II: National Research Council of Canada, Division of Mechanical Engineering Report MH107A.

6. Baird, W.F., 1978. Wave Climate Analysis for Selected Locations in the Gulf of St. Lawrence and Lake Superior: Marine Directorate Report, Public Works Canada, August 1978.

7. Baird, W.F. and J.S. Readshaw, 1981. A Comparison of Hindcast and Recorded Wave Data. Marine Environmental Data Service, Department of Fisheries and Oceans, Contractor Report No. 1, May 1981.

8. Bales, S.L., Cummins, W.E., and Comstock, E.N., 1980. Potential Impact of Twenty Year Hindcast Wind and Wave Climatology on Ship Design, S.N.A.M.E., Chesapeake Section Meeting, September 17, 1980.

9. Born, G.H., J.A. Dunne and D.B. Lame, 1979. SEASAT mission overview, Science, Vol. 204, No. 4400, 29 June 1979, p. 1405-1407.

10. Brown, O.B. and R.E. Cheney, 1983. Advances in satellite oceanography, in U.S. National Report of the 18th General Assembly, International Union of Geodesy and Geophysics, Hamburg, 15-27 August, 1983, p. 1216-1230.

11. Cardone, V. and Ross, D.B., State-of-the-Art Wave Prediction Methods and Data Requirements. Proceedings of the Ocean Wave Climate Symposium, pages 39-60, 1977.

12. Cardone, V.J., W.J. Pierson and E.G. Ward, 1976. Hindcasting the Directional spectrum of hurricane generated waves. J. of Petrol. Technology, 28 April, pp. 385-394.

13. Chen, H.T., and Hoffman, D. The Implementation of the 20-year Hindcast Wave Data in the Design and Operation of Marine Structures. Offshore Technology Conference, Vol. 4, page 2495, 1979.

14. Corson, W.D., Resio, D.T., Brooks, R.M., Ebersole, B., and Jensen, R.E. Atlantic Coast Hindcast, Deepwater Significant Wave Information, U.S. Army Waterways Experiment Station, 891 pages, January, 1981.

15. Corson, W.D. and Resio, D.T. Comparison of Hindcast and Measured Deepwater Significant Wave Heights, U.S. Army Corps Waterways Experiment Station, Wave Information Studies of U.S. Coastlines, WIS Report 3, 41 pages, 1981.

16 Cummins, W.E., and Bales, S.L. Extreme Value and Rare Occurrence Wave Statistics for Northern Hemispheric Shipping Lanes. Proceedings - 5th Ship Technology and Research Symposium, pages 219-239, June, 1980.

17. Det Norske Veritas, 1977. Rules for the Design Construction and Inspection of Offshore Structures (Reprint with corrections 1981).

18. Det Norske Veritas, 1977. Rules for the Design Construction and Inspection of Offshore Structures. Appendix A Environmental Conditions (Reprint with corrections 1982).

19. Det Norske Veritas, 1977. Rules for the Design Construction and Inspection of Offshore Structures. Appendix B Loads (Reprint with corrections 1982).

20. Draper, L. 1972. Extreme Wave Conditions in British and Adjacent Waters. Proceedings of 13 Coastal Engineering Conference July 1972.

21. Group Five Consulting Ltd. 1978. Extreme Wave Conditions in the Labrador Sea, A Hindcast Analysis Using Synoptic Weather Maps. Report submitted to Total Eastcan Exploration Ltd., February 1978.

22. Hammett, D.S. 1983. Future semi-submersible drilling units. RINA Offshore Engineering Group Int. Symposium: Semi-submersibles the New Generation, March 1983.

23. Haring, R.E. 1979. Extreme Wave Statistics Based on NORSWAM Hindcast Results. International Conference on Sea Climatology, Paris, October 1979.

24. Hodgins, D. 1984. Shallow Water Wave Calculations. Canadian Contractor Report of Hydrography and Ocean Sciences, No. 10.

25. Hoffman, D. and Chen, H.H. The Use of Directional Hindcast Spectra as Design Wave Spectra. Offshore Technology Conference, Vol. 4, pages 1989-2001, 1978.

26. Hogben, N. and Lumb. Ocean Wave Statistics. Her Majesty's Stationary Office, London, 1967.

27. Huang, N.E. 1979. New developments in satellite oceanography and current measurements, in U.S. National Report of the 17th General Assembly of the International Union of Geodesy and Geophysics, Canberra, 2-15 December, 1979, p. 1558-1568.

28. Jardine, T.P. The Reliability of Visually Observed Wave Heights. Coastal Engineering, Vol. 3, pp. 33-38, 1979.

29. Lazanoff, S.M. and Stevenson, M.M. A Twenty Year Northern Hemisphere Wave Spectral Climatology. Proceedings of the NATO Symposium on

Turbulent Fluxes Through the Sea Surface, Wave Dynamics and Prediction, France, September, 1977.

30. Neu, H.J.A. 1982. 11 Year Deep-Water Wave Climate of Canadian Atlantic Waters. Can. Tech. Rep. Hydrog. Ocean Sci. 13: vii + 41 p.

31. Nordenstrom, N. 1975. A Method to Predict Long Term Distributions of Waves and Wave Induced Motions and Loads on Ships and Other Floating Structures. Norske Veritas Report No. 81, April, 1975.

32. Oceanweather Inc. 1982. Hibernia Wave Hindcast Study. Final Report (Confidential). Submitted to Mobil Oil Canada, March, 1982.

33. Ochi, M.K. Wave Statistics for the Design of Ships and Ocean Structures. Proc. SNAME. Paper presented in New York, November, 1978.

34. Permanent International Association of Navigation Congresses, 1973. Report of the International Commission for the Study of Waves. Excerpt from Bulletin No. 15, Vol. II, 1973.

35. Pierson, W.J. and R.E. Salfi, 1978. Verification Results for Spectral Ocean Wave Model (SOWM) by Means of Significant Wave Height Measurements Made by the GEOS-3 Spacecraft. NASA Report NASA-CR-62089, p. 236.

36. Pierson, W.J. The Spectral Ocean Wave Model (SOWM). A Northern Hemisphere Computer Model for Specifying and Forecasting Ocean Wave Spectra, David Taylor Naval Ship Research and Development Centre, Report DTNSRDC-82/001, 1982.

37. Resio, D.T. 1982. Assessment of Wave Hindcast Methodologies in the Scotian Shelf, Grand Banks and Labrador Sea Areas. Can. Contract. Rep. Hydrog. Ocean Sci. 4: 128 p.

38. Wilson, J.R. 1983. Hindcasting Waves from Winds for the East Coast of Canada. Proceedings Oceans 83, San Francisco, August 1983.

# APPENDIX A

# DESIGN PROCEDURES

# AND

# REQUIREMENTS FOR WAVE DATA

## APPENDIX A

## INDEX

Appendix A

## Design & Analysis Procedures involving Wave Data

In this Appendix published requirements of the industry for wave data in the design, classification and regulatory processes are quoted from referenced documents. While all published documents could not be reviewed during the course of this study, the following provides a representative perspective of current design practice and the requirement for wave data.

### A.1. Stability in Extreme Conditions

#### A.1.1 Fixed Structures

**Design:**

(i) American Petroleum Institute

API (1982) states the following concerning requirements for wave data:

*Available statistical data and or realistic statistical and mathematical models should be utilized to develop the description of operating and extreme environmental conditions.*

1. *Operating environmental conditions (conditions which are expected to occur frequently during the life of the structure) are important both during the construction and the service life of a platform.* (operating environmental conditions are discussed in this Appendix in section A-3).

2. *Extreme conditions (conditions which recur quite rarely during the life of the structure) are important in formulating platform design loadings.*

*All data used should be carefully documente The estimated reliability and the source of all data should be noted and the methods employed in developing available data into the desired environmental values should be defined.*

*Wind-driven waves are a major source of environmental forces on offshore platforms. Such waves are irregular in shape, can vary from one or more directions simultaneously. For these reasons the intensity and distribution of the forces applied by waves are difficult to determine. Because of the complex nature and the technical factors which must be considered in developing wave-dependent criteria for the design of platforms, experienced specialists knowledgeable in the fields of meteorology, oceanography, and hydrodynamics should be consulted.*

*In those areas where prior knowledge of oceanographic conditions is insufficient, the development of wave dependent design parameters should include at least the following steps:*

1. *Development of all necessary meteorological data.*

2. *Theoretical projection of surface wind fields.*

3. *Theoretical prediction of deepwater general sea-states along storm tracks.*

4. *Definition of maximum possible sea-states consistent with geographical limitations.*

5. *Delineation of bathymetric effects on deepwater sea-states.*

6. *Introduction of probabilistic techniques to predict sea-state occurrences at the platform site against various time bases.*

7. *Development of design wave parameters through physical and economic risk evaluation.*

*In areas where considerable previous knowledge and experience with oceanographic conditions exist, the foregoing sequence may be shortened to those steps needed to project this past knowledge into the required design parameters.*

*It is the responsibility of the platform owner to select the design sea-state, after considering all of the factors listed. In developing sea-state data, consideration should be given to the following:*

*For extreme conditions:*

*Definition of the extreme sea-states should provide an insight as to the number, height, and crest elevations of all waves above a certain height which might approach the platform site from any direction during the entire life of the structure.*

*Projected extreme wave heights from specified directions should be developed and presented graphically vs. their expected average recurrence intervals. Other data which should be developed includes:*

1. *The probable range and distribution of wave periods associated with extreme wave heights.*

2. *The projected distribution of other wave heights in the wave train producing an extreme wave height(s).*

3. *The maximum crest elevations of the extreme sea-states.*

4. *The tides, currents, and winds which potentially occur simultaneously with the wave trains producing the extreme waves.*

5. *The nature, date and place of the event which produced the historical sea-states (e.g. Hurricane Edith, September 16, 1971, Gulf of Mexico) used in the development of the projected values.*

*Alternately, this sea-state data could be presented in spectral format by plots of sea-state energy content vs. expected average return intervals.*

*Also of value to the platform designer (and/or owner) when performing risk analyses would be predictions of the number of extreme sea-states (containing wave heights or crest elevations exceeding a specific lower bound) from various directions which could be expected at the site during the life of the platform.*

*At the option of the design engineer, this wave information can be extended by a qualified hydrodynamist into pressure field or wave force data for selected sea-states. These data can be supplied in either conventional (at points in time) or spectral format.*

With respect to the loads produced by waves API (1982) states the following:

*Environmental loads are loads imposed on the platform by natural phenomena including wind, current, wave, earthquake, snow, ice and earth movement. Environmental loads also include the variation in hydrostatic pressure and buoyancy on members caused by changes in the water level due to waves and tides.*

*Environmental loads, with the exception of earthquake load, should be combined in a manner consistent with the probability of their simultaneous occurrence during the loading condition being considered.*

*The wave loads on a platform are dynamic in nature. For most design water depths presently encountered, these loads may be adequately represented by their static equivalents. For deeper waters or where platforms tend to be more flexible, the static analysis may not adequately describe the true dynamic loads induced in the platform. Correct analysis of such platforms requires a load analysis involving the dynamic action of the structure.*

***Static Wave Analysis***

1. ***Design Wave Parameters.*** *Generally the design wave(s), as selected by the platform owner, is described by the parameters of wave height, wave period, and total water depth. Alternately, design wave(s) may be specified (by the platform owner) by means of the frequency distribution of its energy content (spectral format). In either case, the values specified should be consistent with the intended use of the structure.*

2. ***Wave Force on a Member.*** *The computation of the force exerted by waves on a cylindrical object is dependent upon the ratio of the wave length to the member diameter. When this ratio is large, it may be assumed that the member does not significantly modify the incident wave. The wave force on a cylindrical object is computed as the sum of a drag force, which is related to the kinetic energy of the water, and an inertial force which is related to the acceleration of the water. This force is given by...*

$$F = F_D + F_I = C_D \frac{w}{2g} DU|U| + C_M \frac{w}{g} \frac{\pi}{4} D^2 \frac{dU}{dt}$$

*where:*

$F$ = *hydrodynamic force vector per unit length acting normal to the axis of the member, lb/ft (N/m)*

$F_D$ = *drag force vector per unit length acting normal to the axis of the member, lb/ft (N/m)*

$F_I$ = *inertia force vector per unit length acting normal to the axis of the member, lb ft (N/m)*

$C_D$ = *drag coefficient*

$w$ = *weight density of water, $lb/ft^3 (N/m^3)$*

$g$ = *gravitational acceleration, $ft/sec^2$ $(m/s^2)$*

$D$ = *diameter of cylindrical member, ft (m)*

$U$ = *component of the velocity vector of the water normal to the axis of the member, ft/sec (m/s)*

$|U|$ = *absolute value of U, ft sec (m/s)*

$C_M$ = *mass coefficient*

$\frac{dU}{dt}$ = *component of the acceleration vector of the wave normal to the axis of the member, $ft/sec^2$ $(m/s^2)$*

*Water particle velocity and acceleration are functions of wave height, wave period, water depth, distance above bottom, and time. These functions may be determined by any defensible method.*

3. ***Wave Position (Horizontal) Relative to Structure.*** *The wave crest should be positioned relative to the structure so that the wave forces have their maximum horizontal effect on the structure. Maximum stress in a locally sensitive portion of the structure may occur for a wave position, height, or period other than that causing maximum total force on the structure as a whole.*

***Dynamic Wave Analysis***

1. ***General.*** *A dynamic analysis of a fixed platform is indicated when the design sea-state contains significant wave energy at frequencies near the platform's natural frequencies. The wave energy content versus frequency can be described by wave (energy) spectra as determined from measured data or predictions appropriate for the platform site. Dynamic analyses should be performed for guyed towers.*

2. ***Waves.*** *Use of a random wave theory is appropriate for dynamic analysis of fixed platforms. The regular wave theories above may be used if they adequately define the frequency distribution of wave*

*force for platform modes that contribute significantly to the platform dynamic response.*

3. ***Currents.*** *Currents should be added to the wave kinematics.*

4. ***Winds.*** *For analysis of template, tower or caisson platforms, member forces due to wind loading may be superimposed.*

   *For guyed towers, the analysis should include the simultaneous action of wind, waves and current. It may be appropriate to consider wind dynamics.*

5. ***Fluid Force on a Member.*** *Equation 2.3.1 (of API 1982) may be used to compute forces on member of template, tower, or caisson platforms. For guyed towers this equation should be modified to account for relative velocity by making the following substitution in the drag force term.*

   *replace* $U|U|$ *by* $(U-\dot{x})|U-\dot{x}|$

   *where* $\dot{x}$ = *component of structural velocity normal to the axis of the member, ft/sec (M/S)*

   $U$ = *as defined*

   *This relative velocity formulation may also be used for template, tower, or caisson platforms having large deflections in which case damping values should be adjusted.*

   *Fluid forces associated with the platform acceleration are accounted for by added mass.*

6. ***Structural Modeling.*** *The dynamic model of fixed platforms should reflect the key analytical parameters of mass, damping, and stiffness. The mass should include that of the platform steel, all appurtenances, conductors, and deck loads, the mass of water enclosed in submerged tubular members, and the added mass of submerged members.*

   *Equivalent viscous damping values may be used in lieu of an explicit determination of damping components. In the absence of substantiating information for damping values for a specific structure, a damping value of five percent of critical for extreme wave and two percent of critical for fatique analyses may be used. If relative velocity is considered in the wave force computation, reductions should be made in the damping values.*

   *For guyed towers, response to extreme waves may be predicted ignoring structural damping. In the absence of substantiating information for damping values for a specific guyed tower, a damping value of one percent of critical may be used for fatigue analyses.*

   *The analytical model should include the elastic stiffness of the platform and reflect the structure foundation interaction. It may be*

*appropriate to consider a stiffer foundation for fatigue analyses than for extreme wave response analyses. For guyed towers, these stiffnesses should be augmented to account for the guyline system. Analysis procedures may be required that account for the dynamic interaction of the tower and guyline system. All guyed tower analytical models should include geometric stiffness (large displacement effects). Forces affecting geometric stiffness include gravity loads, buoyancy, the vertical component of the guyline system reaction, and the weight of conductors including their contents.*

7. ***Analysis Methods.*** *Time history methods of dynamic analysis are preferred for predicting the extreme wave response of template platforms, caissons, and guyed towers because these structures are generally drag force dominated. The non-linear system stiffness also indicates time domain analysis for guyed towers. Frequency domain methods may be used for extreme wave response analysis if linearization of the drag force can be justified: for guyed towers, both the drag force and non-linear guyline stiffness methods are generally appropriate for small wave fatigue analysis.*

   *For member design, stresses may be determined from static analyses which include in an appropriate manner the significant effects of dynamic response determined from separate analyses made according to the provisions of this Section.*

***Deck Clearance.*** *Large forces on a platform may result when waves strike a platform's lower deck and the concentration of equipment thereon. With the appropriate provisions made for increases in water depth due to storm and astronomical tides, and platform installation-water depth determination allowances, the guideline wave heights together with the applicable wave theories and wave periods determined from specified wave steepness may be used to compute deck clearance elevations.*

*Referenced level deck clearance elevations are shown in table 2.3.4* (of API 1982). *These elevations are determined by the crest height associated with the reference level wave height and wave steepness, the storm and astronomical tidal heights, plus an appropriate safety allowance.*

*Provisions should be made for wave forces developed on deck components and equipment placed below the anticipated crest elevation associated with the guidelines wave heights.*

**Classification:**

(i) American Bureau of Shipping (ABS)

ABS (1983) states the following concerning environmental design criteria:

*The combination and severity of environmental conditions for use in design are to be appropriate to the problem being considered and consistent with the probability of simultaneous occurrence of the*

*environmental phenomena. It is to be assumed that environmental phenomena may approach the installation from any direction unless reliable site-specific data indicate otherwise. The direction, or combination of directions, which produces the most unfavorable effects on the installation is to be accounted for in the design.*

***Design Environmental Condition***

*In these Rules, the combination of environmental factors producing the most unfavorable effects on the structure, as a whole and as defined by the parameters given below, is referred to as the Design Environmental Condition. This condition is to be described by a set of parameters representing the most severe environmental condition expected to occur during the life of the structure and will normally be composed of:*

*a. The maximum wave height corresponding to the selected recurrence period together with the associated wind, current and limits of water depth, and appropriate ice and snow effects.*

*b. The extreme air and sea temperatures.*

*c. The maximum water level due to tide and storm surge.*

*However, depending upon site-specific conditions, consideration should be given to permutations of the combinations of events contained in item* **a** *above. The recurrence period chosen for events* **a**, **b**, *and* **c** *above is normally not to be less than one hundred years, unless justification for a reduction can be provided.*

***Specific Environmental Conditions***

***Waves***

*a.* ***General*** *Statistical wave data from which design parameters are determined are normally to include the frequency of occurrence of various wave height groups, associated wave periods and directions. Published data and previously established design criteria for particular areas may be used where such exist. Hindcasting techniques which adequately account for shoaling and fetch limited effects on wave conditions at the site may be used to augment available data. Analytical wave spectra employed to augment available data are to reflect the shape and width of the data, and they are to be appropriate to the general site conditions.*

*b.* ***Long-Term Predictions*** *All long-term and extreme-value predictions employed for the determination of design wave conditions are to be fully described and based on recognized techniques. Design wave conditions may be formulated for use in either deterministic or probabilistic methods of analysis, but the method of analysis is to be appropriate to the specific topic being considered.*

*c.* ***Data*** *The development of wave data to be used in required analyses is to reflect conditions at the installation site and the type of structure.*

*As required, wave data may have to be developed to determine the following:*

*Deck level clearance and provision for air gap*
*Maximum mud line shear force and overturning moment*
*Dynamic response of the structure*
*Maximum stress, dynamic amplification, impact and fatigue of local structure*

*Breaking wave criteria are to be appropriate to the installation site and based on recognized techniques. Waves which cause the most unfavorable effects on the overall structure may differ from waves having the most severe effects on individual structural components. In general, more frequent waves of lesser heights, in addition to the most severe wave conditions, are to be investigated when fatigue and dynamic analyses are required.*

With respect to loads produced by waves, ABS (1983) note the following:

*Environmental loads are loads due to wind, waves, current, ice, snow, earthquake, and other environmental phenomena. The characteristic parameters defining an environmental load are to be appropriate to the installation site. Operating Environmental Loads are those loads derived from the parameters characterizing Operating Environmental Conditions. Design Environmental Loads are those loads derived from the parameters characterizing the Design Environmental Condition.*

*Environmental loads are to be applied to the structure from directions producing the most unfavorable effects on the structure, unless site-specific studies provide evidence in support of a less stringent requirement.*

*Model or field test data may be employed to establish environmental loads. Alternatively, environmental loads may be determined using analytical methods compatible with the data established. Any recognized load calculation method may be employed provided it has proven sufficiently accurate in practice, and it is shown to be appropriate to the structure's characteristics and site conditions. The calculation methods presented herein are offered as guidance representative of current acceptable methods.*

***Wave Loads***

*a.* ***Range of Wave Parameters*** *A sufficient range of realistic wave periods and wave crest positions relative to the structure are to be investigated to ensure an accurate determination of the maximum wave loads on the structure. Consideration should be given to other wave induced effects such as wave impact loads, dynamic amplification and fatigue of structural members. The need for analysis of these effects is to be assessed on the basis of the configuration and behavioral characteristics of the structure, the wave climate and past experience.*

*b.* ***Determination of Wave Loads*** *For structures composed of members having diameters which are less than 20% of the wave lengths being*

considered, semi-empirical formulations such as Morison's equation are considered to be an acceptable basis for determining wave loads. For structures composed of members whose diameters are greater than 20% of the wave lengths being considered, or for structural configurations which substantially alter the incident flow field, diffraction forces and the hydrodynamic interaction of structural members are to be accounted for in design.

c. **Morison's Equation** The hydrodynamic force acting on a cylindrical member, as given by Morison's equation, is expressed as the sum of the force vectors indicated in the following equation.

$$F = F_D + F_I$$

$F$ = hydrodynamic force vector per unit length along the member, acting normal to the axis of the member

$F_D$ = drag force vector per unit length

$F_I$ = inertia force vector per unit length

The drag force vector for a stationary, rigid member is given by

$$F_D = (\gamma/2g)\ DC_D\ u_n|u_n|$$

$\gamma$ = weight density of water, in $N/m^3$ $(lb/ft^3)$

$g$ = gravitational acceleration, in $m/s^2$ $(ft/s^2)$

$D$ = projected width of the member in the direction of the cross-flow component of velocity (in the case of a circular cylinder, $D$ denotes the diameter), in m (ft)

$C_D$ = drag coefficient (dimensionless)

$u_n$ = component of the fluid velocity vector normal to the axis of the member, in m/s (ft/s)

$|u_n|$ = absolute value of $u_n$, in m/s (ft/s)

The inertia force vector for a stationary, rigid member is given by

$$F_I = (\gamma/g)\ (\pi D^2/4)\ C_M\ a_n$$

$C_m$ = inertia coefficient based on the displaced mass of fluid per unit length (dimensionless)

$a_n$ = component of the fluid acceleration vector normal to the axis of the member, in $m/s^2$ $(ft/s^2)$

For compliant structures which exhibit substantial rigid body oscillations due to the wave action, the modified form of Morison's equation given below may be used to determine the hydrodynamic force.

$$F = F_D + F_I = (\gamma/2g)\ DC_D(u_n - u'_n)\ |u_n - u'_n|$$

$$+ (\gamma/g)\ (\pi D^2/4)a_n + (\gamma/g)\ (\pi D^2/4)\ C_m\ (a_n - a'_n)$$

$u'_n$ = component of the velocity vector of the structural member normal to its axis, in m/s (ft/s)

$C_m$ = added mass coefficient, i.e., $C_m = C_M - 1$

$a'_n$ = component of the acceleration vector of the structural member normal to its axis, in $m/s^2$ $(ft/s^2)$

For structural shapes other than circular cylinders, the term in the above equations is to be replaced by the actual cross-sectional area of the shape.

Values, of $u_n$ and $a_n$ for use in Morison's equation are to be determined using a recognized wave theory appropriate to the wave heights, wave periods, and water depth at the installation site. Values for the coefficients of drag and inertia to be used in Morison's equation are to be determined on the basis of model tests, full scale measurements, or previous studies which are appropriate to the structural configuration, surface roughness, and pertinent flow parameters (e.g., Reynolds number).

Generally, for pile-supported template type structures, values of $C_D$ range between 0.6 and 1.2; values of $C_M$ range between 1.5 and 2.0.

d. **Diffraction Theory** For structural configurations which substantially alter the incident wave field, diffraction theories of wave loading are to be employed which account for both the incident wave force (i.e., Froude-Krylov force) and the force resulting from the diffraction of the incident wave due to the presence of the structure.

The hydrodynamic interaction of structural members is to be taken into account. For structures composed of surface piercing caissons or for installation sites where the ratio of water depth to wave length is less than 0.25, nonlinear effects of wave action are to taken into account. This may be done by modifying linear diffraction theory to account for nonlinear effects or by performance of model tests.

*Air Gap*

*An air gap of at least 1.5 m (5 ft) is to be provided between the maximum wave crest elevation and the lowest protuberance of the superstructure for which wave forces have not been included in the design. After accounting for the initial and expected long-term settlements of the structure, due to consolidation and subsidence in an oil reservoir area, the design wave crest elevation is to be superimposed on the still water level and consideration is to be given to wave run-up, tilting of the structure and, where appropriate, tsunamis.*

(ii) Det Norske Veritas (DnV)

DnV (1982) states the following concerning the required wave data:

*Wave conditions may be described either by statistical or deterministic methods. The validity of the procedures used is to be documented.*

*The selection of suitable parameters for design purposes is in both cases to be based on the use of wave statistics or accepted hindcasting techniques.*

*Analytical wave power density spectra are to reflect the width and shape of typical spectra for the site considered. For open sea areas, the Pierson-Moskowitz type of spectrum will normally apply. Other spectrum formulations will be considered under special circumstances.*

*The short-crestedness of waves in a seaway, i.e., the angular distribution of wave energy, may be taken into account. If detailed field measurements are not available a cosine squared distribution will normally be accepted.*

*Extreme values of wave heights are to be expressed in terms of most probable largest values with their corresponding recurrence periods.*

*Long-term predictions are to be based on recognized techniques.*

*In design using deterministic procedures based on regular wave considerations, the wave is to be described by the parameters H and T. The design wave formulation used is to be valid for the problem considered.*

*The design waves or sea states are to be those resulting in the most unfavourable effects on the structure or structural part considered, taking into account the shape and size of the structure, water depth, etc. Consideration is to be given to the probability of occurence of these design waves or sea states.*

*The wave period is to be specified in each case of application. It may be necessary to investigate the wave loads for a range of wave periods in order to ensure a sufficiently accurate determination of the maximum response. Normally, it will suffice to consider the following range of wave periods.*

*Deterministic approach:*

$$\sqrt{6.5H} < T < \sqrt{15H}$$

*Stochastic approach:*

$$\sqrt{13H_s} < T_p < \sqrt{30H_s}$$

*The wave field should be described by wave theories relevant to the conditions at the site considered.*

*The still water level to be used in wave load calculations for storm conditions is defined as the more unfavourable of either the highest astronomical tide level plus increase in water depth due to wind and pressure induced storm surge, or the lowest astronomical tide level.*

In addition to the above DnV provide the following guidance concerning wave conditions:

**A2 WAVES**

**A2.1.1 Wave Data**

**A2.1.1 Instrumental wave data**

*A2.1.1.1 Wave statistics should preferably be based on instrumentally recorded data.*

*A2.1.1.2 Attention should be given to derive relevant parameters from the recordings such as:*

| | |
|---|---|
| $H_s$ | *significant wave height* |
| $T_z$ | *average zero-upcrossing wave period* |
| $T_c$ | *average period between wave crests* |
| $\varepsilon$ | *spectral width* |
| $T_p$ | *period of spectral peak* |
| $S(\omega)$ | *spectral shape* |

**A2.1.2 Visual wave data**

*A2.1.2.1 When wave statistics are presented in terms of visual observed wave heights and periods $H_V$, $T_V$, these data may be transformed to*

*estimates of significant wave height $H_s$ and average zero-upcrossing period $\overline{T}_z$ at the same probability level by the following relationships:*

$$H_s = 1.68\, H_V^{0.75} \tag{A2-1}$$

$$T_z = 0.82\, T_V^{0.96} \tag{A2-2}$$

*As Eqs. A2-1 and A2-2 are based on transformation on the same probability level, they are strictly applicable to statistical distributions only and not necessarily to individual sea state data.*

*A2.1.2.2 Other formulae than Eqs. A2-1 and A2-2 may be used if shown to be appropriate for the site considered.*

**A2.2 Short term wave statistics**

*A2.2.1 Short term stationary irregular sea states may be described by wave power density spectra such as the Pierson-Moskowitz or the Jonswap spectrum.*

*A2.2.2 In general, the modified Pierson-Moskowitz spectrum will apply. However, the Jonswap spectrum may also be used if shown to be more appropriate for the site considered.*

*A2.2.3 The modified Pierson-Moskowitz spectrum may be written in non-dimensional form as:*

$$\frac{S(\omega)}{h_s^2 T_z} = \frac{1}{8\pi^2}\left(\frac{\omega T_z}{2\pi}\right)^{-5} \exp\left[\frac{-1}{\pi}\left(\frac{\omega T_z}{2\pi}\right)^{-4}\right] \tag{A2-3}$$

*where*

| | |
|---|---|
| $H_s$ | *significant wave height* |
| $S(\omega)$ | *power spectral density* |
| $T$ | *wave period* |
| $T_z$ | *average zero-upcrossing wave period* |
| $\omega$ | *angular wave frequency* $\left(\omega = \frac{2\pi}{T}\right)$ |

A2.2.4 The Jonswap spectrum in dimensional form is written:

$$S(f) = \alpha \cdot g^2 \cdot (2\pi)^{-4} f^{-5} \; exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \cdot FAC \qquad \text{(A2-4)}$$

$$FAC = \gamma^{exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right]} \qquad \text{(A-2-5)}$$

where

$f$ frequency (hz)

$f_p$ frequency of spectral peak (hz)

$g$ acceleration due to gravity ($m/sec^2$)

$\alpha$ Phillips' constant

$\sigma$ spectral width parameter
$\sigma = 0.07$ if $f \leq f_p$
$\sigma = 0.09$ if $f > f_p$

$\gamma$ peakedness parameter.

A2.2.5 Special attention should be given to the variation of the parameters $\alpha$ and $\gamma$ in Eqs. A2-4 and A2-5, respectively, when using the Jonswap spectrum.

A2.2.6 Directional short-crested wave power density spectra may be derived from the unidirectional long-crested wave power density spectra given in A2.2.3 and A2.2.4 as follows:

$$S(\omega, \alpha) = S(\omega) \; f(\alpha) \qquad \text{(A2-6)}$$

where

$\alpha$ angle between direction of elementary wave trains and the main direction of the short-crested wave system

$S(\omega, \alpha)$ directional short-crested wave power density spectrum

$S(\omega)$ unidirectional long-crested wave power density spectrum

$f(\alpha)$ directionality function.

Energy conservation requires that the directionality function fulfills the following requirement:

$$\int_{\alpha_{MIN}}^{\alpha_{MAX}} f(\alpha)d\alpha = 1 \qquad \text{(A2-7)}$$

A2.2.7 In the absence of more reliable data the following directionality function may be applied:

$$f(\alpha) = {}^{2}\ \cos^2 \alpha \ \text{for} \ -\pi/2 \leq \alpha \leq \pi/2 \qquad \text{(A2-8)}$$

A2.2.8 Other directionality functions than given in A2.2.7 may be accepted if shown to be appropriate for the site considered.

A2.2.9 The statistical distribution of individual wave heights in an irregular short-term stationary sea state may usually be described by the Rayleigh distribution.

**A2.3 Long-term wave statistics**

A2.3.1 The significant wave height $H_S$ versus probability of exceedance $Q(H_S)$ and the frequency distribution $p(\bar{T}_Z)$ of the average zero-upcrossing wave period $\bar{T}_Z$ may be obtained from the wave statistics. Examples are shown in Figures A.1 and A.2.

A2.3.2 Provided that the statistics of $H_S$ may be described by a two-parameter Weibull distribution function, the wave height $H_n$ at a probability level $Q=10^{-n}$ is found from:

$$H_n = \frac{a \cdot b_1}{\sqrt{2}} (2,3 \cdot n)^{k_1} \qquad \text{(A2-9)}$$

The coefficients $b_1$ and $k_1$ are given in a table, and depend on the parameter "m" defined in another figure A.2. The parameter "a" is also defined.

A2.3.3 The "N year wave", i.e. the most probable largest individual wave height during N years, may be found by introducing the following value for n in Eq. A2-9.

$$n = 6,7 + \log_{10}N \qquad \text{(A2-10)}$$

*A2.3.4 When the value $H_r$ at a reference probability level $Q = 10^{-r}$ is given, the value $H_n$ at another probability level $10^{-n}$ is found from Eq. A2-11.*

$$H_n = H_r \left(\frac{n}{r}\right)^{k_1} \tag{A2-11}$$

*Some data for the most probable largest wave heights in 100 years are given in table A4 (DnV 1982). The probability level $Q = 10^{-8.7}$, which corresponds to once in a period of 100 years, is chosen as a reference level (r=8,7).*

With respect to loads produced by waves DnV notes the following:

*Wave induced loads are to be determined by use of generally recognized methods taking proper account of water depth, size, shape and type of structure.*

*In the analytical determination of wave loads, the hydrodynamic coefficients used in the analysis may be determined on the basis of published data, model tests, or full scale measurements. The hydrodynamic coeffiecients are subject to approval.*

*For structures of complex shape for which analytical determination of wave loads may not yield sufficient accuracy, the wave loads are to be determined by use of reliable and adequate model tests.*

*The following contributions are to be considered in the determination of wave induced loads;*

- *potential pressure forces including the Froude-Krilov forces*
- *potential or viscous wave drift forces*
- *drag forces resulting from boundary layer effects*
- *impact loads*

*Wave induced loads on structures consisting of members with cross sectional dimensions less than aproximately 1/5 of the wavelength may be calculated by use of Morison's equation.*
*The combined effect of simultaneous drag and inertia forces is obtained by vectorial addition.*

*Where appropriate, account is to be taken of possible change in water particle velocity and acceleration caused by the structure interfering with the wave system.*

*In lieu of more exact data, the hydrodynamic coefficients used in Morison's equation may be taken.*

*Closely spaced members may cause solidification effects. In lieu of more exact data the formulae given in Appendix B may be used for selection of appropriate hydrodynamic coefficients for such cases.*

*For structures having characteristic dimensions which are not negligible compared to the wave length and which will influence the flow field, the determination of wave loads will normally require application of methods such as sink-source techniques or finite fluid element methods.*

*Hydrodynamic interaction between large immersed members of the structure are to be considered where such effects may be significant.*

*Impact loads from waves are to be determined according to recognized theoretical methods or according to relevant data from model tests or full scale measurements. Attention is to be paid to possible dynamic amplification of the response.*

*The possibility of flow induced cyclic loads is to be considered.*

In addition to the above DnV provide the following guidance concerning the calculation of wave loads.

### B2 WAVE LOADS

#### B2.1 Wave loads on slender members

*B2.1.1 Wave loads on slender members having cross-sectional dimensions sufficiently small to allow the gradients of liquid particle accelerations and velocities in the direction normal to the member to be neglected, may be calculated using Morison's equation. Normally, Morison's equation is applicable when the following condition is satisfied:*

$$\lambda > 5\ D$$

*where*

$\lambda$ — *the wave length*

$D$ — *diameter or other projected cross-sectional dimension of a structural member.*

*B2.1.2 In cases where Morison's equation is applicable, the inertia force may be calculated by the formula:*

$$F_m = \rho\ V\ a + \rho C_m\ V_R\ a_r \qquad \text{(B2-1)}$$

*where*

$F_m$ — *inertia force acting normal to the axis of the member. If sectional hydrodynamic added mass coefficient and volume per unit length are used $F_m$ is a force per unit length. If three-dimensional hydrodynamic added mass coefficient and complete volume of member are used $F_m$ is the total force on the member.*

$\rho$ mass density of fluid

$C_m$ two- or three-dimensional added mass coefficient. In general $C_m$ is a function of cross-sectional shape and orientation of body, Reynold's number, Keulegan-Carpenter number and roughness. $C_m$ values as function of the former two factors are usually accepted.

$a_r$ relative acceleration between liquid particle and member normal to the member axis.

$V$ volume or sectional volume (volume per unit length) of the liquid displaced by the member.

$V_R$ a reference volume (total or sectional) to which the hydrodynamic added mass coefficient may be related.

B2.1.3 Tentative values of $C_m$ for different cross-sectional shapes are given in tables for two- and three-dimensional bodies respectively. These values are based on potential theory and are thus only accounting for cross-sectional shapes and orientation. Other values for $C_m$ may be used provided that the chosen values can be justified.

The $C_m$ value is to be used in conjunction with the acceleration of water particles as calculated using an appropriate wave theory.

B2.1.4 In the cases where Morison's equation is applicable the drag force may be calculated by the formula:

$$F_D = \frac{1}{2} \rho \, C_D \, v_r \, |v_r| \, A \qquad \text{(B2-2)}$$

where

$F_D$ drag force normal to the axis of the member.

$C_D$ drag coefficient for the flow normal to the member axis.

$\rho$ mass density of liquid.

$v_r$ liquid particle velocity relative to the member normal to the member axis.

$|v_r|$ absolute value of $v_r$ introduced to obtain proper sign of $F_D$.

$A$ area of member taken as the projection on a plane normal to the force direction.

B2.1.5 Two-dimensional drag coefficient for smooth circular cylinders in steady uniform flow as a function of Reynold's number is given in Figure B.1 (DnV 1982).

*B2.1.6 Tentative values of hydrodynamic drag coefficients for a circular cylinder of various roughnesses in steady flow are shown in figure B-2 (DnV 1982). The roughness is expressed as the roughness number $k_r/D$ where $k_r$ is the effective roughness height and $D$ diameter of member. In absence of more reliable data on the roughness number, $k_r/D = 1.10^{-2}$ may be used to account for marine growth.*

*Tentative values of drag coefficients in the supercritical regime in steady flow for some in-service-marine-roughnesses are given in figures B-3 (DnV 1982).*

*B2.1.7 Tentative values for the hydrodynamic drag coefficient $C_D$ for other smooth cross-sectional shapes in steady flow may be chosen equal to corresponding values for the wind shape coefficient given in tables B-2 and B-4 (DnV 1982).*

*B2.1.8 Hydrodynamic drag coefficients for a rough cylinder in oscillating flow are subject to approval in each case.*

*The drag coefficient for a smooth cylinder in oscillating flow should not be less than 0.7.*

*B2.1.9 When using Morison's equation to calculate the hydrodynamic loads on a structure one should preferably take into account the variation of $C_D$ as function of Reynold's number, the Keulegan-charpenter number and the roughness number in addition to the variation of cross sectional geometry.*

### *B2.2 Impact Loads From Waves*

#### *B2.2.1 Slamming*

*B2.2.1.1 Horizontal members in the splash zone are susceptible to forces caused by wave slamming when the member is being submerged. The dynamic response of the member should be accounted for.*

*B2.2.1.2 For a horizontal member the slamming force per unit length may be calculated as:*

$$F_s = \frac{1}{2} \rho \, C_s D v^2 \qquad \text{(B2-3)}$$

*where*

| | |
|---|---|
| $F_s$ | *slamming force per unit length in the direction of the velocity.* |
| $\rho$ | *mass density of fluid.* |
| $C_s$ | *slamming coefficient.* |
| $D$ | *member diameter.* |
| $v$ | *velocity of water surface normal to the surface of the member.* |

*B2.2.1.3 The slamming coefficient $C_s$ may be determined using theoretical and/or experimental methods. For smooth, circular cylinders the value of $C_s$ should not be taken less than 3.0.*

*B2.2.1.4 As the slamming force is impulsive, dynamic amplification must be considered when calculating the response.*

*For a horizontal member fixed at both ends, dynamic amplification factors of 1.5 and 2.0 are recommended for the end moments and the midspan moment, respectively.*

*B2.2.1.5 It is generally recognized that wave slamming may cause fatigue. A procedure for evaluating the fatigue effects is outlined in Appendix C (DnV 1982).*

***B2.2.2 Shock Pressure From Breaking Waves***

*B2.2.2.1 Breaking waves causing shock pressures on vertical surfaces should be considered.*

*B2.2.2.2 In absence of more reliable methods the procedure described in B2.2.1.2 may be used to calculate the shock pressure.*

*B2.2.2.3 The coefficient $C_s$ depends on the configuration of the area exposed to shock pressure. A lower limit of $C_s$ for circular cylinders is 3.0. The coefficient $C_s$ is subject to approval by DnV.*

*B2.2.2.4 The area exposed to shock pressure may be taken as a sector of 45 degrees with a height of 0.25 $H_{nB}$, where $H_{nB}$ is the most probable largest breaking wave height in n years. The region from SWL to the top of the wave crest should be investigated for the effects of shock pressure.*

*B2.2.2.5 The impact velocity, v, should be taken as that corresponding to the most probable largest breaking wave height in n years. The most probable largest breaking wave height may be taken as 1.4 times the most probable largest significant wave height in n years.*

## A.1.2 Floating Structures

**Design:**

No publications prepared for use by design organizations, other than those prepared by the Classification Societies, were reviewed during this study.

**Classification:**

(i) American Bureau of Shipping (ABS).

ABS 1980 states that for purposes of classifying mobile drilling units the following are to be included in the owners submission.

*A description of environmental conditions including minimum anticipated atmospheric and sea temperatures, for each mode of operation.*

*Resultant forces and moments from wind, waves, current, mooring and other environmental loadings.*

*Submitted calculations are to be suitably referenced. Results from model tests or dynamic response calculations may be submitted as alternatives or a substantiation for required calculations.*

With regard to the calculation of wave loadings ABS 1980 states:

*Wave criteria specified by the Owner may be described by means of wave energy spectra or by theoretical waves having shape, size, and period appropriate to the depth of water in which the unit is to operate. Waves are to be considered as coming from any direction relative to the unit. Consideration is to be given to waves of less than maximum height where due to their period, the effect on various structural elements may be greater.*

*Examples of wave theories are given in Appendix A,* (of ABS 1980) *and force coefficients for use therein are also given. Consideration will be given to any other valid theoretical approach, or authoritative test data. Examples of calculating the forces resulting from waves are indicated in Appendix A,* (of ABS 1980) *using the method appropriate to the depth of water selected. In making the calculations, the minimum drag coefficient* $C_D$ *is to be the same as* $C_S$ *from Tables provided and the minimum inertia coefficient* $C_m$ *is to be obtained from Tables provided.*

*Wave Induced Vibrations. Consideration is to be given to the possibility of structural vibrations induced by the action of waves.*

Part 1 of Appendix A (of ABS 1980) provides methods for calculating drag forces and moments, and inertia forces and moments on vertical cylinders in shallow water using an interpolation between the solitary and Airy Theories, and several others.

Part 2 of Appendix A (of ABS 1980) contains a development of the sine wave theory for deep water waves which may be used to determine the drag and inertial forces on the underwater portions of drilling units, which may be operating in locations where the depth of water exceeds three hundred feet. The appendix notes that other methods of determining the force which may be deemed appropriate will be considered provided they are referenced and supported by calculations.

With regard to underdeck clearance ABS 1980 states:

*A crest clearance of either 1.2m (4 ft) or 10% of the combined storm tide, astronomical tide, and height of the maximum wave crest above the mean low water level, whichever is less, between the underside of the*

*unit in the elevated position and the crest of the wave is to maintained. This crest elevation is to be measured above the level of the combined astronomical and storm tides.*

(ii) Det Norske Veritas (DnV)
DnV (1982) provide the following description of the required wave conditions.

*All environmental phenomena which may contribute to structural damages are to be considered. Such phenomena are wind, waves, currents, ice, earthquake, soil conditions, temperature, fouling, corrosion, etc.*

*The specified environmental design data used for calculating design loads for intact structure are to correspond with the most probable largest values for a return period of 100.*

*For damaged structure calculations a return period of one year is to be used.*

*The environmental design data may be given as maximum wave heights with corresponding periods and wind and current velocities and design temperatures or as acceptable geographical areas for operation. In the latter case the Builder is to specify the operational areas and submit documentation showing that the environmental data for these areas are within the environmental design data.*

*The statistical data used as a basis for design must cover a sufficiently long period of time.*

*The liquid particle velocity and acceleration in regular waves are to be calculated according to recognized wave theories, taking into account the significance of shallow water and surface elevation.*

*Linearized wave theories may be used when appropriate. In that case the particle velocity in the wave crest above still water level is normally to be taken equal to the velocity at the still water level.*

*The wave design data are to represent the maximum wave heights specified for the unit, as well as the maximum wave steepness.*

*The wave lengths are to be selected as the most critical ones for the response of the structure or structural part to be investigated.*

*Breaking wave height as a function of still water depth is given in Fig. 1.* (of DnV 1982)

*Guidance:*

*For unrestricted operation the wave steepness with return period 100 years may normally be limited according to:*

*Regular design wave:*
*The maximum regular wave height as function of wave period:*

$$H_w = \begin{cases} 0.22T^2 & \text{for } T \leq 6\text{s} \\ \dfrac{T^2}{4.5+0.02(T^2-36)} & \text{for } T>6\text{s} \end{cases}$$

$T$ = *design wave period in s.*
$H_w$ = *design wave height in m.*

*Short term irregular states of sea:*
*The sea state steepness is not to be less than:*

$$S = \frac{2\pi}{g_o}\frac{H_s}{T_z^2} = \begin{cases} 1/10 \text{ for } T_z < 6\text{s} \\ 1/15 \text{ for } T_z \geq 12\text{s} \\ \text{Linear interpolation for } 6 < T_z < 12\text{s} \end{cases}$$

*which may be expressed in terms of significant wave height:*

$$H_s = \begin{cases} 0.156\ T_z^2 \text{ for } T_z \leq 6\text{s} \\ 0.206\ T_z^2 - 0.0086\ T_z^3 \text{ for } 6<T_z \leq 12\text{s} \\ 0.104\ T_z^2 \text{ for } T_z > 12\text{s} \end{cases}$$

*$H_S$ and $T_Z$ are defined in Sec. 3 B 302.*

*The maximum wave height corresponding to formulae above need normally not be taken larger than 32 m.*

*Wave conditions which are to be considered for design purposes, may be described either by deterministic design wave methods or by stochastic methods applying wave energy spectra.*

*Short term irregular states of sea are described by means of wave energy spectra which are characterized by significant wave height ($H_S$), and average zero-up-crossing period ($T_Z$).*

*Analytical spectrum expressions are to reflect the width and shape of typical spectra for the considered site. For open deep-water sea areas, the Pierson-Moskowitz type of spectrum will normally apply. For shallow water a more narrow spectrum may be used when found appropriate (e.g. a Jonswap spectrum).*

*The shortcrestedness of waves in a seaway, i.e. the directional disperision of wave energy, may be taken into account. The principal direction of wave encounter is defined as the direction of maximum wave energy density.*

*The modified Peirson-Moskowitz spectrum may be written in non-dimensional form as:*

$$\frac{S(\omega)}{H_s^{\,2} T_z} = \frac{1}{8\pi^2} \left(\frac{\omega T_z}{2\pi}\right)^{-5} \exp\left[\frac{-1}{\pi}\left(\frac{\omega T_z}{2\pi}\right)^{-4}\right]$$

*The Jonswap spectrum in dimensional form is written:*

$$S(f) = \alpha . g_o^{\,2} . (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] .\mathrm{FAC}$$

$$\mathrm{FAC} = \gamma \exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^{\,2}}\right]$$

*Special attention should be given to the variation of the parameters $\alpha$ and $\gamma$ when using the Jonswap spectrum.*

*Definitions:*

| | | |
|---|---|---|
| $H_w$ | = | *the individual wave height in m, i.e. the vertical distance from crest to trough.* |
| $H_s$ | = | *the average of the highest one third of the individual wave heights in m in a short term stationary state of sea (significant wave height).* |
| $T$ | = | *the average zero-up-crossing period in s.* |
| $S(\omega)$ | = | *power spectral density.* |
| $T_z$ | = | *wave period in s.* |
| $\omega$ | = | *angular wave frequency* $\left(\omega = \frac{2\pi}{T}\right)$ |
| $f_p$ | = | *frequency (Hz).* |
| $f$ | = | *frequency of spectral peak (Hz).* |
| $\alpha$ | = | *Phillips' constant.* |

$\sigma$ = *spectral width parameter.*

= $0{,}07$ *if* $f \leq f_p$.

= $0{,}09$ *if* $f > f_p$.

$\gamma$ = *peakedness parameter.*

*The long term behaviour of the sea is described by means of a family of wave spectra, the probability of occurrence for each spectrum being taken into account. For this purpose one needs the joint probability density function for* $H_S$ *and* $T_z$, *which can be obtained from wave statistics. A description of the long term state of sea based on the use of hindcastings can also be accepted.*

*Wave statistics for individual principal directions of wave encounter should be used, otherwise conservative assumptions are to be introduced.*

*Extreme wave heights are expressed in terms of wave heights having a low probability of occurrence.*

*The "N year wave height" is the most probable largest individual wave height during N years. This is equivalent to a wave height with a return period of N years.*

*In deterministic design procedures, based on simple regular wave considerations, the wave is to be described by the following parameters:*

- *wave period.*
- *wave height.*
- *wave direction.*
- *still water depth.*

*The choice of an appropriate design wave formulation has to be based on particular considerations for the problem in question. Shallow water effects are to be accounted for. Different wave theories may be accepted by the Society. However, the limitations of the theories used are to be duly acknowledged.*

*The design waves are to be those which produce the most unfavourable loads on the considered structure, taking into account the shape and size of structure, etc.*

*The wave period is to be specified in each case of application. It may be necessary to investigate a representative number of wave periods, in order to ensure a sufficiently accurate dermination of the maximum loads.*

*The basic wave load parameters and response calculation methods in these Rules are to be used together with a deterministic wave load analysis with the most unfavourable combinations of height, period and direction of the waves.*

*If a stochastic wave load analysis is used, a more accurate assessment of load and strength parameters may be required, e.g. to account for marine growth. As an alternative the extreme wave loads may be multiplied with an appropriate load factor.*

*The still water level to be used in wave load calculations for survival condition for self-elevating units, is defined as the high astronomical tide level plus increase in water depth due to wind induced storm surge. If sufficient statistical data are available, the still water level corresponding to a 100-year return period may be used.*
*High and low astronomical tide are the high and low tide due to attraction of the sun and the moon, in contrast to a meteorological tide caused by meteorological conditions.*

## A.2. Fatigue Calculations

The references cited in section A-1 provide little guidance concerning the specific requirements for wave data for fatigue calculations.

The American Bureau of Shipping 1980 states "*When a fatigue analysis is performed, a long term distribution of the stress range, with proper consideration of dynamic effects, is to be obtained for relevant loadings anticipated during the design life of structure,*" Section 6.13 of ABS 1980 Fatigue Assessment states "*For structural members and joints where fatigue is a probable mode of failure, or for which past experience is insufficient to assure safety from possible cumulative fatigue damage, an assessment of fatigue life is to be carried out. Emphasis is to be given to joints and members in the splash zone, those that are difficult to inspect and repair once the structure is in service, and those susceptible to corrosion-accelerated fatigue.*"

"*For structural members and joints which require a detailed assessment of cumulative fatigue damage, the results of the assessment are to indicate a minimum expected fatigue life of twice the design life of the structure where sufficient structural redundancy exists to prevent catastrophic failure of the structure of the member or joint under consideration. Where such redundancy does not exist or where the desirable degree of redundancy is significantly reduced as a result of fatigue damage, the result of a fatigue assessment is to indicate a minimum expected fatigue life of three times the design life of the structure.*

Det Norske Veritas, 1977, provides the following comment on the method of analysis as follows:

"*As most of the loads which contribute to fatigue are of random nature statistical considerations will normally be required for determination of the long term distribution of fatigue loading effects. Deterministic or spectral analysis may be used. The method of analysis used is subject to acceptance.*"

Det Norske Veritas (1982, provides further guidance concerning the required wave statistics:

"*A reasonable number of constant amplitude stress blocks and corresponding number of stress cycles are to be evaluated from a long term stress distribution determined for the planned life of the structures. All direction of wind, waves and current relative to the unit, are normally to be assumed equally probable. If, however, statistics show clearly that wind, waves and current of the prescribed probability are different for different directions, this may be taken into account in the analysis*".

It is concluded that, ideally, fatigue calculations would require directional spectra representative of storm events that produce critical stress levels in typical structures during a minimum of a twenty year period. In practice, bivariate frequency of occurrence (scatter) diagrams of wave height and period parameters (typically characteristic wave height and peak period, presented for directional sectors, are required. These should be based on 20 years of data (as may be achieved from wave hindcast study).

## A-3 Design and Assessment of Operations

There are many modes of operations of a structure designed for the exploration or recovery of hydrocarbons. The primary requirement for wave data is in the determination of the frequency of occurrence and duration of periods when an operation must be restricted for reasons of safety.

ABS 1980 refer to three modes of operations for mobile structure as follows:

a) ***Normal Drilling Conditions*** *Normal drilling conditions are conditions wherein a unit is on location to drill or perform other related operations where the combined environmental and operational loadings are within the appropriate design limits established for those operations. The unit may be either afloat or supported by the sea bed.*

b) ***Severe Storm Condition*** *A severe storm condition is a condition during which a unit may be subjected to the most severe environmental loadings for which it was designed. During the severe storm condition it may be necessary to discontinue drilling or similar operations, due to the severity of the environmental loadings. The unit may be either afloat or supported by the sea bed, as applicable.*

c) ***Transit Conditions*** *All unit movements from one geographical location to another.*

ABS (1983) state the following when referring to fixed structures:

***Operating Environmental Conditions***

*For each intended major function or operation of the installation, a set of characteristic parameters for the environmental factors which act as a limit on the safe performance of an operation or function is to be determined. Such operations may include, as appropriate, transportation, offloading and installation of the structure, drilling or producing operations, evacuation of the platform, etc. These sets of conditions are herein referred to as Operating Environmental Conditions.*

DnV 1980 provide definitions for five design phases. Analysis of downtime during each of these phases may be required and each may require different presentations of wave data. The definitions are as follows:

***Design phases*** *- the design life of an offshore structure is normally divided into five design phases as defined in the following:*

- *Phase C - Construction:*
  *This phase includes construction ashore and construction afloat.*

- *Phase T - Transportation:*
  *This phase includes transportation of the structure or a part of the structure, including transportation from shore to sea, or from shore to barge, and mooring operations in protected waters.*

*Phase I - Installation:*
*This phase includes installation of the structure at its final location, i.e.,*

*the period from start of submerging from transport position or launching from barge, including piling, grouting or anchoring, until the platform is ready for normal operation.*

*Phase O - Operation:*
*This phase is the period from completed installation till condemnation or removal from location.*

*Phase R - Retrieval:*
*This phase includes retrieval or removal of the structure.*

The planning of operations requires a suitable data base from which the frequencies of occurrence of events causing downtime, and their duration, can be determined. It may also be necessary to determine the average duration of continuous periods when no operational restrictions occur.

The characteristics of this data base is that it provides continuous coverage (by observations, recordings or estimates made every 3 hours for example) over a long enough period that statistics representative of an average year may be determined. It is estimated that a three to five year period of measurements is required for this purpose.

It must also be noted that other environmental conditions such as high wind speeds, currents, presence of ice, reduced visibility or low temperatures may restrict operations and simultaneous measurements or estimates may be required for the proper design of operations. The most important phenomena for which simultaneous measurements are required are waves, winds and water currents.

API (1982) provides the following guidance concerning the data and data presentations required for the design and assessment of operations.

*For operating conditions (for both seas and swells):*

1. *For each month and/or season, the probability of occurrence and average duration (persistence data) of various sea-states (e.g., waves higher than 10 ft (3 m) from specified directions in terms of general sea-state description parameters (e.g., the significant wave height/average height of the highest one-third of the waves in the train/and the average wave period during a certain duration of time).*

2. *The wind velocities, tides and currents occurring simultaneously with the wave trains.*

3. *The percentage of waves having heights and directions within specified ranges (e.g., 10 to 12 ft. (3 to 4 m) high waves from SSE + 11.25 ) during each month and/or season.*

## A-4 Requirements of Regulatory Agencies

The regulations developed by the Canadian Oil & Gas Lands Administration (COGLA) do not provide detailed guidance concerning the form of wave data and type of engineering procedures that involve wave data which should be submitted with applications for Drilling Program Approval. Guidance notes that present estimates of the wave climate of Canada are not available as they are for the North Sea.

Some of the requirements contained in the Canada Oil & Gas Drilling regulations (PC 1979-25 ammended by PC 1980-2111) are as follows.

***PART 1***

***Drilling Program Approval***

*Application for a Drilling Program Approval*

8. *The following information shall be furnished and forwarded with the application for approval of a drilling program referred to in section 7 by an applicant:*

   (c) *particulars of any special conditions or circumstances that may affect the safety of the drilling operations;*

   (f) *where the program is to be carried out offshore,*

   (ii) *the prevailing environmental conditions in the area of the program,*

   (g) *in the case of every drilling unit used or intended to be used by an applicant during the program,*

   (ii) *the details of the structural design of the drilling unit on which the applicant relies to show that the drilling unit has strength adequate to withstand conditions of extreme loading caused by a combination of the most unfavourable functional and environmental loads,*

   (iii) *a description of the relationship between the performance characteristics of each drilling unit and the prevailing environmental conditions in the area of the program, and*

   (h) *where the program is to be carried out offshore, the details on which the applicant relies to show that*

   (i) *the drilling unit that is to be used in the program has sufficient dynamic stability to permit emergency drilling operations, such as controlling a kick or disconnecting from the blowout preventer stack, to be conducted under conditions of the statistical one-year-storm calculated to occur during the period of the year that the program is to be conducted,*

   (ii) *where anchors are to be used to hold the drilling unit on the well location, the method and equipment to be used to hold the*

*drilling unit is capable of maintaining the unit within the anchor pattern under conditions of the statistical fifty-year-storm calculated to occur during the period of the year that the program is to be conducted,*

(iii) *the drilling unit to be used in the program is designed and constructed to survive conditions of the statistical one-hundred-year-storm calculated to occur during the period of the year that the program is to be conducted,*

(vi) *the support craft are designed and constructed to operate safely in support of all drilling and related operations in which the craft are to be engaged.*

COGLA have issued "Physical Environmental Guidelines for Drilling Programs in The Canadian Offshore". These guidelines contain standards and procedures for collecting and reporting meteorological and oceanographic data and have been issued with respect to section 176(2) (for example) of the Drilling Regulations. This states, with respect to waves, that where the drilling program is offshore the operator shall observe and record at least every three hours the wave direction, height and period and the swell direction, height and period.

The following contains extracts from these guidelines where they refer to the collection of wave data:

***Physical Environmental Requirements***

***1.0 Data Collection***

*Operators will be required to make meteorological and oceanographic measurements in connection with drilling operations in accordance with these Guidelines unless COGLA has agreed to other arrangements. The standards and procedures for collecting and reporting meteorological and oceanographic data are described below.*

*Automatic instrumentation is the preferred means of measurement; however, cloud conditions, present and past weather, visibility, wave direction, sea ice and ice accretion are normally determined visually and recorded in a log.*

***1.1 Parameters to be Observed or Measured***

*1.1.10* ***Sea State*** *- instantaneous values of sea and swell height, period and direction.*

*1.1.15* ***Surface ocean wave spectra*** *- instrumentation should be located such that the wave field as observed is not disturbed by the drilling unit. The Marine Environmental Data Service (MEDS), Department of Fisheries and Oceans, Ottawa, may provide a Datawell Waverider Buoy for wave measurements. Other instrumentation may be used but the specifications stated must be met and the recording sequence should be consistent with a twenty-minute continuous wave record every three hours and have the capability for continuous operation during storms.*

*Other data collection requirements specified in the guidelines include wind, temperature, visibility, ice, precipitation, and currents.*

# APPENDIX B

## GLOSSARY OF WAVE PARAMETERS

# APPENDIX B

## GLOSSARY OF WAVE PARAMETERS

1. **Parameters defined directly from a wave record.**

$Z_1$ — The "mean water depth" is the vertical distance between the mean water level and the bottom. $Z_1$ is always a positive quantity.

$Z_2$ — The "still water depth" is the vertical distance between the still water level and the bottom. $Z_2$ is always a positive quantity.

$Z_3$ — The "mean record water depth" is the vertical distance between the mean record level and the bottom. $Z_3$ is always a positive quantity.

$\eta$ — The vertical distance of the instantaneous water surface to the mean record level, positive is used for the upward direction.

$a_c$ — The crest amplitude is the vertical distance between the mean record level and a crest or maxima.

$a_{z,c}$ — The zero-crossing crest amplitude is the maximum vertical distance between the mean record level and the maximum level that occurred between an upward and a following downward going zero crossing. $a_{z,c}$ is always a positive quantity.

$a_t$ — The trough amplitude is the vertical distance between the mean record level and a trough or minima.

$a_{z,t}$ — The zero-crossing trough amplitude is the maximum vertical distance between the mean record level and the minimum level that occurred between a downward and a following upward going zero-crossing. $a_{z,t}$ is always a positive quantity.

$Y_1$ — The maximum wave level is the maximum zero-crossing crest amplitude observed in a record = $a_{z,c,max}$

$Y_2$ — The minimum wave level is the maximum zero-crossing trough amplitude observed in a record. Note that $Y_2$ is always positive and is = $a_{z,t,max}$

$H$ — The "wave height" is the vertical distance between a crest and the immediately preceding trough.

$H_z$ — The zero up-crossing wave height is the sum of $a_{z,c}$ and the immediately preceding $a_{z,t}$. (Confusion may exist between the use of Hz for Hertz and $H_z$ for the zero-crossing wave height.)

$H_{max}$ — The maximum wave height is the maximum H as observed in a specified period of time, which should always be stated.

| | |
|---|---|
| $H_{z,max}$ | The maximum zero up-crossing wave height is the maximum $H_z$ as observed in a specified period of time, which should always be stated. |
| $T_z$ | The zero-crossing wave period is the interval of time between two adjacent downward going zero-crossings. |
| $T_{Hz,max}$ | The period of the maximum zero up-crossing wave height is the interval between the preceding and the following downward going zero-crossings of a maximum zero up-crossing wave height. |

2. **Statistical parameters.**

| | |
|---|---|
| $H_{n\%}$ | The wave height exceedance is the value of H exceeded by n% of all waves occurring in a specified period. For example $H_{1\%}$ (20 min.) is the wave height that is exceeded by only 1% of all waves occurring in a 20 min. period of observation. In particular one may use $H_{50\%}$ the median wave height. In some countries, the notation $H_{n\%}$ is used to denote the average of the highest n% of the waves in a record. Care should be exercised to properly interpret the intended meaning in individual publications. |
| $H_{z,n\%}$ | The zero up-crossing wave height exceedance is the value of $H_z$ that is exceeded by n% of all waves occurring in a specified period. |
| $\overline{H}_{1/n}$ | The average of the highest $1/n^{th}$ of the H values for a stated period of time. In some countries, the notation $H_{1/n}$ is used to denote the wave height exceeded by $1/n^{th}$ of the waves. Care should be taken to properly interpret the intended meaning in individual publications. |
| $\overline{H}_{z,1/n}$ | The average of the highest $1/n^{th}$ of the $H_z$ values for a stated period of time. In particular one may use $\overline{H}_{z,1/3}$ (20 min.). |
| $\overline{T}_z$ | The zero-crossing wave period is the average of zero-crossing intervals as obtained by dividing the record duration by the number of times the water elevation crosses the mean record level in one direction. |
| $\overline{T}_c$ | The average crest period is the time obtained by dividing the record duration by the total number of crests in this record. |
| $\varepsilon_T$ | The spectral width parameter (Broadness factor) defined by $\varepsilon_T^2 = 1 - (\overline{T}_c/\overline{T}_z)^2$. |
| p(x) | The probability density function of a wave parameter **x**, such as height or period. |
| P(x) | The distribution function of a wave parameter x and is known as $P(x) = \int_{-\infty}^{x} p(\lambda)\,d\lambda$. |

3. **Parameters derived from the variance spectrum analysis.**

$f_p$ — The peak frequency is the frequency at which the maximum variance spectral density occurs.

$T_p$ — The peak period = $1/f_p$.

$S(f)$ — The variance spectral density function of a wave record is the density distribution of the variance $\eta$ as a function of frequency.

$S(f,\alpha)$ — The directional variance spectral density of a wave record is the density distribution of the variance $\eta$ as a function of frequency and direction.

$m_n$ — The $n^{th}$ moment of the variance spectral density function. $m_n = \int_a^b f^n S(f)\,df$.
Typically $a = 0$ $b = \infty$.

$\sigma$ — The root mean square value is the square root of the variance or the average squared displacement of the water surface from the mean record level $\sigma^2 = \bar{\eta}^2 = m_o$.

$H_{mo}$ — The characteristic wave height = $4*\sigma$ for a stated period of time.

$T_{m_{a,b}}$ — The length of time defined by two spectral moments $m_a$ and $m_b$. In particular, one may use the "average period" defined as $m_o/m_1$ or $m_{-1}/m_o$.

$\varepsilon_s$ — The spectral width parameter defined by

$$\varepsilon_s^2 = \frac{m_o \cdot m_4 - m_2^2}{m_o \cdot m_4}$$

4. **Parameters derived from visual observations.**

$H_v$ — The wave height as estimated from visual observation.

$T_v$ — The wave period as obtained visually.

5. **Significant wave height.**

The current use of this term, significant wave height, is confusing. There appear to be 3 common concepts of significant wave height:

a) the wave height parameter as computed from the RMS-value of the record;

b) the average of the highest one third of the "wave heights" obtained autographically; or

c) the visually estimated wave height following W.M.O. practices.

As noted in the above, the following three definitions are recommended:

| | |
|---|---|
| $H_{m_0}$ | The characteristic wave height = $4*\sigma$ for a stated period of time. |
| $H_{z,1/3}$ | (or $H_3$) The average of the highest one third of the zero up-crossing wave heights for a stated period of time. |
| $H_v$ | The wave height as estimated from visual observation. |

# APPENDIX C

# PERIODS OF COVERAGE FOR MEDS WAVE STATIONS

REFERENCE C81043D01

TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE    ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 019 | ADMIRALS BEACH | 2100 | 47-01-48N | 053-37-18W | 55 | 31/03/74 | 22/01/75 | WR | 80-100% | S |
| 086 | BARROW STRAIT | 2500 | 74-37-00N | 092-20-00W | 46 | 16/08/76 | 20/08/76 | WR | 50-80 % | S |
| 073 | BATTLE ISLAND | 2950 | 48-41-24N | 087-33-06W | 219 | 16/05/73 | 17/11/73 | WR | 80-100% | S |
| 127 | BAY BULLS | 2100 | 47-18-51N | 052-48-39W | 17 | 21/07/77 | 13/11/77 | WR | 80-100% | S |
| 127 | BAY BULLS | 2100 | 47-18-51N | 052-48-39W | 17 | 11/01/78 | 22/01/78 | WR | 0-50 % | S |
| 145 | BEN OCEAN LANCER (ACADIA K-62) | 1800 | 42-51-42N | 061-55-21W | 955 | 03/05/78 | 03/08/78 | WR | 50-80 % | S |
| 141 | BEN OCEAN LANCER (HOPEDALE E-33) | 2100 | 55-52-00N | 058-51-00W | 562 | 18/08/78 | 28/09/78 | WR | 50-80 % | S |
| 138 | BEN OCEAN LANCER (HEKJA) | 2200 | 62-11-08N | 062-58-17W | 360 | 22/07/79 | 10/08/79 | WR | 80-100% | S |
| 138 | BEN OCEAN LANCER (HEKJA) | 2200 | 62-11-08N | 062-58-17W | 360 | 25/07/80 | 05/10/80 | WR | 50-80 % | S |
| 138 | BEN OCEAN LANCER (NORTH BJARNI F-06) | 2100 | 55-31-06N | 057-42-27W | 144 | 27/06/81 | 05/10/81 | WR | 50-80 % | S |
| 166 | BOWDRILL I (BANQUEREAU C-21) | 1800 | 44-10-42N | 058-34-00W | 85 | 07/01/82 | 20/10/82 | WR | 80-100% | S |
| 082 | BURLINGTON (CCIW) | 2950 | 43-20-32N | 079-46-16W | 38 | 31/10/72 | 16/12/72 | WR | 0-50 % | S |
| 082 | BURLINGTON (CCIW) | 2950 | 43-20-32N | 079-46-16W | 38 | 22/08/73 | 18/09/73 | WR | 0-50 % | S |
| 082 | BURLINGTON (CCIW) | 2950 | 43-20-32N | 079-46-16W | 38 | 15/11/73 | 15/12/73 | WR | 0-50 % | S |
| 077 | BURLINGTON (INNER) | 2950 | 43-17-18N | 079-43-06W | 26 | 04/06/76 | 16/06/76 | WR | 0-50 % | S |
| 077 | BURLINGTON (INNER) | 2950 | 43-16-12N | 079-45-24W | 13 | 22/09/76 | 28/09/76 | WR | 0-50 % | S |
| 077 | BURLINGTON (INNER) | 2950 | 43-16-48N | 079-44-18W | 14 | 27/04/77 | 23/11/77 | WR | 50-80 % | S |
| 077 | BURLINGTON (INNER) | 2950 | 43-16-08N | 079-44-03W | 14 | 27/09/78 | 30/11/78 | WR | 50-80 % | S |
| 192 | CANMAR I (UKALERK) | 2800 | 70-11-18N | 132-45-12W | 34 | 07/08/77 | 02/10/77 | WR | 50-80 % | S |
| 192 | CANMAR I (UKALERK) | 2800 | 70-10-03N | 132-44-00W | 31 | 22/07/78 | 04/10/78 | WR | 0-50 % | S |
| 193 | CANMAR II (KOPANOAR) | 2800 | 70-23-54N | 135-06-00W | 64 | 07/08/77 | 01/10/77 | WR | 50-80 % | S |
| 193 | CANMAR II (KOPANOAR) | 2800 | 70-22-54N | 135-05-36W | 57 | 02/09/78 | 04/10/78 | WR | 50-80 % | S |
| 147 | CAPE ENRAGE | 1860 | 45-44-54N | 064-36-24W | 37 | 14/06/78 | 19/02/79 | WR | 50-80 % | S |
| 032 | CAPE ROSEWAY | 1860 | 43-31-18N | 065-12-06W | 37 | 11/06/70 | 29/10/70 | WR | 50-80 % | S |
| 032 | CAPE ROSEWAY | 1860 | 43-31-18N | 065-12-06W | 37 | 08/12/70 | 04/06/72 | WR | 50-80 % | S |
| 022 | CAPE SPEAR | 2100 | 47-31-33N | 052-37-57W | 59 | 08/04/76 | 27/04/76 | WR | 50-80 % | S |
| 042 | CAPE TORMENTINE | 1860 | 46-08-13N | 063-46-23W | 7 | 12/06/73 | 20/11/73 | PC | 50-80 % | S |
| 059 | CAPE TORMENTINE | 2000 | 46-10-00N | 063-45-00W | 17 | 09/07/76 | 17/11/76 | WR | 50-80 % | S |
| 058 | CAPUCINS | 2000 | 49-04-41N | 066-48-54W | 36 | 20/06/75 | 11/11/75 | WR | 50-80 % | S |
| 084 | CHEDABUCTO BAY | 1860 | 45-28-24N | 061-10-30W | 27 | 25/10/74 | 11/02/75 | WR | 50-80 % | S |
| 084 | CHEDABUCTO BAY | 1860 | 45-28-24N | 061-10-30W | 27 | 04/05/75 | 04/02/76 | WR | 50-80 % | S |
| 146 | CHIGNECTO BAY | 1860 | 45-41-28N | 064-32-59W | 11 | 14/06/78 | 06/08/78 | WR | 50-80 % | S |
| 146 | CHIGNECTO BAY | 1860 | 45-33-24N | 064-49-18W | 11 | 06/08/78 | 13/12/78 | WR | 50-80 % | S |
| 064 | COBOURG | 2950 | 43-49-05N | 078-02-05W | 69 | 12/04/72 | 04/12/72 | WR | 80-100% | S |
| 064 | COBOURG | 2950 | 43-53-15N | 078-09-12W | 69 | 29/03/73 | 12/12/73 | WR | 50-80 % | S |
| 159 | CONCEPTION BAY | 2100 | 48-00-00N | 052-30-00W | 176 | 20/10/81 | 22/10/81 | WR | 50-80 % | S |
| 072 | COVE ISLAND | 2950 | 45-19-24N | 081-56-18W | 65 | 26/05/73 | 17/11/73 | WR | 50-80 % | S |
| 027 | CSS DAWSON (MINAS BASIN) | 2000 | 45-17-25N | 064-09-05W | 18 | 30/06/75 | 01/12/75 | WR | 50-80 % | S |
| 027 | CSS DAWSON (MINAS BASIN) | 2000 | 45-17-25N | 064-09-05W | 18 | 13/04/76 | 23/11/76 | WR | 80-100% | S |
| 150 | CSS DAWSON (EMERALD BASIN) | 1860 | 43-55-24N | 062-38-12W | 190 | 16/11/79 | 21/11/79 | WR | 50-80 % | S |
| 021 | DEADMANS BAY | 2100 | 47-32-36N | 052-39-30W | 53 | 08/04/76 | 27/04/76 | WR | 50-80 % | S |
| 131 | DISCOVERER 7-SEAS (BLUE H-28) | 1800 | 49-37-34N | 049-18-29W | 1524 | 16/05/79 | 17/08/79 | WR | 80-100% | S |
| 080 | EDDY POINT | 1860 | 45-31-06N | 061-14-05W | 46 | 31/05/72 | 15/02/73 | WR | 50-80 % | S |
| 200 | EXPLORER I | 2800 | 70-31-07N | 133-20-05W | 46 | 03/08/79 | 10/09/79 | WR | 50-80 % | S |
| 200 | EXPLORER I | 28[illegible] | 70-05-00N | 136-40-00W | N/A | 11/08/80 | 18/09/80 | WR | 50-80 % | S |

TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE          ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 201 | EXPLORER II (TARSUIT) | 2800 | 69-58-08N | 136-36-09W | 30 | 13/08/79 | 18/09/79 | WR | 80-100% | S |
| 201 | EXPLORER II | 2800 | 70-34-00N | 134-35-00W | N/A | 16/08/80 | 13/09/80 | WR | 50-80 % | S |
| 201 | EXPLORER II (ISSUNGNAK) | 2800 | 70-05-00N | 134-26-00W | 27 | 28/07/81 | 31/08/81 | WR | 50-80 % | S |
| 201 | EXPLORER II (IRKALUK) | 2800 | 70-35-00N | 134-14-00W | 58 | 28/07/82 | 21/08/82 | WR | 0-50 % | S |
| 201 | EXPLORER II (AIVERK) | 2800 | 70-26-30N | 133-59-00W | 60 | 02/09/82 | 29/09/82 | WR | 50-80 % | S |
| 196 | EXPLORER III (KAGLULIK) | 2800 | 70-34-06N | 130-51-24W | 27 | 31/08/78 | 01/09/78 | WR | 50-80 % | S |
| 196 | EXPLORER III (KOAKOAK) | 2800 | 70-28-00N | 134-06-00W | 60 | 07/08/81 | 06/10/81 | WR | 50-80 % | S |
| 196 | EXPLORER III (NERLERK) | 2800 | 70-24-48N | 133-27-00W | 52 | 27/07/82 | 25/08/82 | WR | 80-100% | S |
| 196 | EXPLORER III (ORVILRUK) | 2800 | 70-22-30N | 136-32-00W | 58 | 01/09/82 | 29/09/82 | WR | 50-80 % | S |
| 202 | EXPLORER IV | 2800 | 70-49-00N | 130-18-00W | N/A | 15/08/80 | 07/09/80 | WR | 50-80 % | S |
| 202 | EXPLORER IV (KILANNAK) | 2800 | 70-46-00N | 129-21-00W | 25 | 05/08/81 | 14/08/81 | WR | 50-80 % | S |
| 202 | EXPLORER IV (KENALOOK) | 2800 | 70-44-00N | 133-50-00W | 71 | 25/07/82 | 27/07/82 | WR | 80-100% | S |
| 124 | FISHERMANS COVE (K) | 2900 | 49-21-18N | 123-16-28W | 6 | 06/04/79 | 27/03/80 | ST | 80-100% | S |
| 123 | FISHERMANS COVE (WB) | 2900 | 49-21-00N | 123-42-00W | 50 | 11/04/79 | 27/03/80 | WR | 50-80 % | S |
| 045 | FOX RIVER A | 2000 | 49-00-19N | 064-23-00W | 8 | 15/05/74 | 10/07/74 | WR | 50-80 % | S |
| 045 | FOX RIVER A | 2000 | 49-00-18N | 064-23-17W | 18 | 15/05/75 | 10/11/75 | WR | 50-80 % | S |
| 045 | FOX RIVER A | 2000 | 49-00-19N | 064-23-00W | 9 | 19/07/78 | 05/12/78 | WR | 80-100% | S |
| 162 | FOX RIVER A(K) | 2000 | 48-59-45N | 064-23-03W | 4 | 30/06/78 | 05/12/78 | ST | 0-50 % | S |
| 046 | FOX RIVER B | 2000 | 48-59-08N | 064-23-00W | 5 | 24/05/74 | 18/09/74 | PC | 80-100% | S |
| 163 | FOX RIVER B(K) | 2000 | 48-59-43N | 064-23-11W | 3 | 04/07/78 | 20/09/78 | ST | 80-100% | S |
| 047 | FOX RIVER C | 2000 | 48-59-47N | 064-23-17W | 3 | 15/05/75 | 10/11/75 | WR | 50-80 % | S |
| 114 | FRENCH CREEK (INNER) | 2900 | 49-21-02N | 124-21-15W | 4 | 24/11/76 | 24/02/77 | WR | 50-80 % | S |
| 115 | FRENCH CREEK (OUTER) | 2900 | 49-21-02N | 124-21-15W | 7 | 24/11/76 | 15/03/77 | WR | 80-100% | S |
| 028 | GABARUS BAY | 1860 | 45-49-36N | 060-04-48W | 24 | 28/05/75 | 12/02/76 | WR | 80-100% | S |
| 028 | GABARUS BAY | 1860 | 45-49-36N | 060-04-48W | 24 | 29/04/76 | 13/01/77 | WR | 80-100% | S |
| 026 | GABARUS BAY | 1860 | 45-49-40N | 060-03-40W | 33 | 28/04/76 | 12/01/77 | WR | 50-80 % | S |
| 121 | GIBSONS LANDING | 2900 | 49-24-00N | 123-30-00W | 37 | 30/03/78 | 03/04/79 | WR | 50-80 % | S |
| 071 | GIMLI | 2960 | 50-38-55N | 096-54-00W | 9 | 15/09/71 | 07/11/71 | WR | 50-80 % | S |
| 071 | GIMLI | 2960 | 50-38-55N | 096-54-00W | 9 | 10/06/72 | 23/10/72 | WR | 50-80 % | S |
| 036 | GLACE BAY | 1860 | 46-13-30N | 059-26-15W | 46 | 02/12/70 | 11/01/71 | WR | 80-100% | S |
| 036 | GLACE BAY | 1860 | 46-08-00N | 059-30-00W | 46 | 23/04/71 | 04/10/71 | WR | 80-100% | S |
| 136 | GLOMAR ATLANTIC (HIBERNIA P-15) | 1851 | 46-46-20N | 048-46-00W | 82 | 01/06/79 | 21/10/79 | WR | 80-100% | S |
| 136 | GLOMAR ATLANTIC (SOUTH LABRADOR N-79) | 2100 | 55-48-50N | 058-26-37W | 490 | 31/07/80 | 25/09/80 | WR | 50-80 % | S |
| 067 | GODERICH (INNER) | 2950 | 43-44-42N | 081-43-21W | 7 | 14/08/72 | 07/12/72 | PC | 80-100% | S |
| 068 | GODERICH (OUTER) | 2950 | 43-44-46N | 081-43-49W | 7 | 14/08/72 | 07/12/72 | PC | 80-100% | S |
| 069 | GODERICH (WB) | 2950 | 43-44-49N | 081-44-27W | 8 | 02/09/72 | 07/12/72 | WR | 50-80 % | S |
| 009 | GRAND BAY (INNER) | 2000 | 47-34-36N | 059-12-36W | 14 | 05/10/74 | 17/12/74 | WR | 50-80 % | S |
| 010 | GRAND BAY (OUTER) | 2000 | 47-35-00N | 059-17-40W | 91 | 27/04/74 | 17/12/74 | WR | 50-80 % | S |
| 070 | GRAND BEACH | 2960 | 50-38-55N | 096-38-30W | 9 | 22/06/71 | 10/11/71 | WR | 50-80 % | S |
| 070 | GRAND BEACH | 2960 | 50-38-55N | 096-38-30W | 9 | 18/05/72 | 23/10/72 | WR | 80-100% | S |
| 070 | GRAND BEACH | 2960 | 50-38-55N | 096-38-30W | 9 | 22/05/73 | 05/06/73 | WR | 80-100% | S |
| 190 | GULF I | 2800 | 70-03-30N | 133-39-00W | 33 | 15/08/77 | 13/10/77 | WR | 50-80 % | S |
| 191 | GULF II | 2800 | 70-08-24N | 136-24-48W | 43 | 16/08/77 | 10/10/77 | WR | 50-80 % | S |
| 144 | GULF TIDE (THEBAUD I-94) | 1800 | 43-44-00N | 060-20-30W | 60 | 09/03/78 | 06/11/78 | WR | 80-100% | S |
| 144 | GULF TIDE (VENTURE D-23) | 1800 | 43-47-30N | 059-37-00W | 60 | 06/11/78 | 10/06/79 | WR | 0-50 % | S |

CANADIAN MARINE DATA INVENTORY REPORT

D. HISTORICAL WAVE MEASURING STATIONS

REFERENCE C81043D01



TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE    ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 002 | GUYANA | 1850 | 07-24-28N | 058-18-00W | 14 | 22/02/74 | 19/03/74 | WR | 50-80 % | S |
| 097 | HALIBUT BANK | 2900 | 49-20-36N | 123-44-06W | 53 | 11/01/74 | 16/05/74 | WR | 80-100% | S |
| 129 | HARBOUR GRACE | 2100 | 47-41-21N | 053-12-44W | 17 | 11/06/78 | 24/07/78 | WR | 50-80 % | S |
| 129 | HARBOUR GRACE | 2100 | 47-40-39N | 053-14-09W | 10 | 24/07/78 | 16/02/79 | WR | 80-100% | S |
| 094 | HAVDRILL (BONAVISTA C-99) | 2100 | 49-08-06N | 051-14-27W | 335 | 09/07/74 | 03/10/74 | WR | 50-80 % | S |
| 094 | HAVDRILL (BONAVISTA C-99) | 2100 | 49-08-00N | 051-14-00W | 335 | 11/06/75 | 11/08/75 | WR | 80-100% | S |
| 094 | HAVDRILL (INDIAN HARBOUR M-52) | 2100 | 54-21-51N | 054-23-49W | 196 | 17/08/75 | 21/10/75 | WR | 50-80 % | S |
| 089 | HAY RIVER | 2960 | 60-57-24N | 115-42-45W | 18 | 18/06/75 | 30/09/75 | WR | 80-100% | S |
| 098 | HERSCHEL ISLAND | 2800 | 69-00-00N | 139-00-00W | N/A | 01/08/70 | 30/08/70 | WR | 0-50 % | S |
| 194 | ISSERK | 2800 | 69-57-30N | 134-26-00W | 14 | 11/08/77 | 16/09/77 | WR | 0-50 % | S |
| 198 | ISSUNGNAK | 2800 | 70-04-00N | 132-27-00W | 24 | 04/08/78 | 13/08/78 | WR | 50-80 % | S |
| 198 | ISSUNGNAK | 2800 | 70-03-20N | 133-59-36W | 24 | 19/08/79 | 15/10/79 | WR | 50-80 % | S |
| 205 | ITIYOK ISLAND (ESSO) | 2800 | 69-56-58N | 134-29-40W | 14 | 03/08/82 | 26/09/82 | WR | 50-80 % | S |
| 063 | KINCARDINE (INNER) | 2950 | 44-10-36N | 081-38-24W | 3 | 07/10/73 | 18/12/73 | PC | 50-80 % | S |
| 062 | KINCARDINE (OUTER) | 2950 | 44-10-48N | 081-38-48W | 6 | 20/10/73 | 18/12/73 | PC | 50-80 % | S |
| 113 | KINCOLITH | 2900 | 54-59-51N | 129-58-48W | 37 | 06/10/77 | 26/02/78 | WR | 80-100% | S |
| 074 | KINGSTON | 2950 | 44-06-20N | 076-34-58W | 30 | 25/07/73 | 30/11/73 | WR | 80-100% | S |
| 074 | KINGSTON | 2950 | 44-06-03N | 076-35-04W | 29 | 27/06/75 | 08/08/75 | WR | 50-80 % | S |
| 074 | KINGSTON | 2950 | 44-06-03N | 076-35-04W | 29 | 09/06/76 | 08/09/76 | WR | 50-80 % | S |
| 118 | KITIMAT | 2900 | 53-58-52N | 128-39-12W | 37 | 08/10/77 | 22/03/78 | WR | 80-100% | S |
| 160 | LAMEQUE (K) | 2000 | 47-46-15N | 064-39-36W | 4 | 29/09/81 | 21/12/81 | ST | 0-50 % | S |
| 057 | LES ESCOUMINS | 2000 | 48-12-06N | 069-18-55W | 91 | 29/04/74 | 30/09/74 | WR | 80-100% | S |
| 057 | LES ESCOUMINS | 2000 | 48-13-39N | 069-16-18W | 91 | 01/10/74 | 07/11/74 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-38-18N | 052-28-18W | 168 | 01/08/72 | 14/12/72 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-38-12N | 052-27-48W | 168 | 22/06/73 | 20/01/74 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-38-12N | 052-27-48W | 168 | 25/06/74 | 22/01/75 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-38-12N | 052-27-48W | 168 | 06/06/75 | 13/01/76 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-36-06N | 052-26-40W | 167 | 18/06/76 | 31/01/77 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-36-06N | 052-26-40W | 167 | 09/06/77 | 09/01/78 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-37-00N | 052-25-27W | 166 | 16/06/79 | 13/02/80 | WR | 80-100% | S |
| 016 | LOGY BAY | 2100 | 47-37-00N | 052-25-27W | 166 | 18/05/80 | 31/12/80 | WR | 50-80 % | S |
| 016 | LOGY BAY | 2100 | 47-37-00N | 052-25-27W | 162 | 01/01/81 | 04/03/82 | WR | 80-100% | S |
| 016 | LOGY BAY | 2100 | 47-37-00N | 052-25-27W | 162 | 07/06/82 | 28/01/83 | WR | 50-80 % | S |
| 117 | LUND | 2900 | 49-58-52N | 124-45-58W | 37 | 12/10/77 | 25/03/78 | WR | 80-100% | S |
| 148 | LUNENBERG (K) | 1860 | 44-22-30N | 064-18-30W | 6 | 14/12/78 | 06/11/79 | ST | 80-100% | S |
| 149 | LUNENBERG (WB) | 1860 | 44-21-06N | 064-17-36W | 12 | 14/12/78 | 27/11/79 | WR | 50-80 % | S |
| 015 | M V TYPHOON (LEIF M-48) | 2100 | 54-17-00N | 055-07-00W | 30 | 21/07/71 | 02/09/71 | WR | 50-80 % | S |
| 164 | MAGDALEN ISLANDS | 2000 | 47-20-00N | 061-46-48W | 14 | 29/05/81 | 02/09/81 | WR | 50-80 % | S |
| 164 | MAGDALEN ISLANDS | 2000 | 47-28-12N | 061-37-48W | 18 | 19/05/82 | 26/08/82 | WR | 50-80 % | S |
| 048 | MAGDALEN (INNER) | 2000 | 47-38-01N | 061-31-10W | 13 | 28/06/76 | 19/11/76 | WR | 50-80 % | S |
| 048 | MAGDALEN (INNER) | 2000 | 47-38-12N | 061-31-02W | 13 | 02/07/77 | 29/11/77 | WR | 50-80 % | S |
| 048 | MAGDALEN (INNER) | 2000 | 47-38-06N | 061-31-00W | 13 | 16/07/78 | 07/12/78 | WR | 80-100% | S |
| 043 | MAGDALEN (OUTER) | 2000 | 47-36-06N | 061-18-04W | 27 | 23/05/74 | 17/12/74 | WR | 80-100% | S |
| 043 | MAGDALEN (OUTER) | 2000 | 47-36-06N | 061-18-04W | 27 | 26/06/75 | 14/12/75 | WR | 50-80 % | S |
| 043 | MAGDALEN (OUTER) | 2000 | 47-36-06N | 061-18-04W | 27 | 28/06/76 | 19/11/76 | WR | 50-80 % | S |

FORM FF A002

CANADIAN MARINE DATA INVENTORY REPORT

D. HISTORICAL WAVE MEASURING STATIONS

REFERENCE C81043D01



TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE     ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 043 | MAGDALEN (OUTER) | 2000 | 47-36-06N | 061-18-04W | 27 | 02/07/77 | 21/07/77 | WR | 50-80 % | S |
| 043 | MAGDALEN (OUTER) | 2000 | 47-37-18N | 061-18-18W | 15 | 14/07/78 | 08/12/78 | WR | 80-100% | S |
| 060 | MAIN DUCK ISLAND | 2950 | 43-47-45N | 076-49-39W | 69 | 19/04/72 | 21/11/72 | WR | 80-100% | S |
| 054 | MATANE | 2000 | 48-50-31N | 067-34-45W | 7 | 26/07/72 | 23/10/72 | ST | 0-50 % | S |
| 206 | MCINLEY BAY | 2800 | 69-58-06N | 131-12-39W | 8 | 07/08/82 | 06/10/82 | WR | 50-80 % | S |
| 085 | MELFORD POINT | 1860 | 45-32-15N | 061-17-43W | 29 | 10/12/74 | 08/02/75 | WR | 0-50 % | S |
| 085 | MELFORD POINT | 1860 | 45-32-15N | 061-17-43W | 29 | 11/04/75 | 04/02/76 | WR | 80-100% | S |
| 044 | MISCOU ISLAND | 2000 | 48-10-30N | 064-16-00W | 46 | 30/05/74 | 21/11/74 | WR | 80-100% | S |
| 135 | NEDDRILL II (ROBERVAL C-02) | 2100 | 54-51-37N | 054-44-41W | 273 | 06/07/80 | 03/09/80 | WR | 50-80 % | S |
| 135 | NEDDRILL II (BJARNI O-82) | 2100 | 55-31-35N | 057-40-38W | 156 | 16/09/80 | 17/10/80 | WR | 50-80 % | S |
| 135 | NEDDRILL II (CORTE REAL P-85) | 2100 | 56-05-20N | 058-12-12W | 438 | 16/07/82 | 31/07/82 | WR | 50-80 % | S |
| 135 | NEDDRILL II (CORTE REAL P-85) | 2100 | 56-05-37N | 058-12-08W | 445 | 23/08/82 | 12/09/82 | WR | 50-80 % | S |
| 135 | NEDDRILL II (CORTE REAL P-85) | 2100 | 56-05-22N | 058-11-31W | 445 | 30/09/82 | 14/10/82 | WR | 80-100% | S |
| 155 | NEDDRILL II-B (ROBERVAL C-02) | 2100 | 54-52-30N | 055-45-06W | 285 | 22/08/80 | 08/09/80 | WR | 50-80 % | S |
| 156 | OCEAN RANGER (HIBERNIA G-55) | 1851 | 46-43-36N | 048-53-30W | 80 | 04/12/80 | 23/02/81 | WR | 50-80 % | S |
| 156 | OCEAN RANGER (HIBERNIA K-18) | 1851 | 46-47-58N | 048-47-58W | 80 | 02/03/81 | 05/06/81 | WR | 50-80 % | S |
| 156 | OCEAN RANGER (SHERIDAN J-87) | 1851 | 48-26-50N | 049-57-58W | 209 | 25/06/81 | 04/11/81 | WR | 50-80 % | S |
| 156 | OCEAN RANGER (HIBERNIA J-34) | 1851 | 46-43-57N | 048-50-43W | 78 | 13/12/81 | 09/02/82 | WR | 50-80 % | S |
| 037 | OSBORNE HEAD | 1860 | 44-32-40N | 063-27-50W | 30 | 12/12/70 | 29/12/70 | WR | 50-80 % | S |
| 037 | OSBORNE HEAD | 1860 | 44-32-40N | 063-27-50W | 30 | 06/03/71 | 15/02/73 | WR | 80-100% | S |
| 037 | OSBORNE HEAD | 1860 | 44-32-49N | 063-27-32W | 30 | 27/02/73 | 28/01/75 | WR | 80-100% | S |
| 037 | OSBORNE HEAD | 1860 | 44-32-49N | 063-27-32W | 30 | 03/03/75 | 01/09/76 | WR | 80-100% | S |
| 037 | OSBORNE HEAD | 1860 | 44-29-25N | 063-24-15W | 57 | 01/09/76 | 31/12/80 | WR | 80-100% | S |
| 037 | OSBORNE HEAD | 1860 | 44-29-25N | 063-24-15W | 57 | 01/01/81 | 31/12/81 | WR | 80-100% | S |
| 154 | PACNORSE I (RUT H-11) | 2100 | 59-10-18N | 062-16-47W | 137 | 27/07/81 | 31/08/81 | WR | 50-80 % | S |
| 154 | PACNORSE I (RUT H-II) | 2100 | 59-10-30N | 062-17-45W | 124 | 06/08/82 | 11/10/82 | WR | 50-80 % | S |
| 083 | PARKER POINT | 1860 | 45-21-21N | 061-19-40W | 37 | 30/11/73 | 16/01/74 | WR | 50-80 % | S |
| 083 | PARKER POINT | 1860 | 45-21-21N | 061-19-40W | 37 | 06/06/74 | 10/12/74 | WR | 80-100% | S |
| 137 | PELERIN (SKOLP E-07) | 2100 | 58-26-00N | 061-46-00W | 75 | 20/08/78 | 17/09/78 | WR | 50-80 % | S |
| 137 | PELERIN (ROBERVAL K-92) | 2100 | 55-00-00N | 055-30-00W | 269 | 16/07/79 | 01/10/79 | WR | 50-80 % | S |
| 137 | PELERIN (OGMUND E-72) | 2100 | 57-31-30N | 060-26-36W | 159 | 16/08/80 | 08/10/80 | WR | 50-80 % | S |
| 137 | PELERIN (NORTH LEIF I-05) | 2100 | 54-25-00N | 055-15-00W | 146 | 08/07/81 | 28/09/81 | WR | 50-80 % | S |
| 137 | PELERIN (POTHURST P-19) | 2100 | 58-48-54N | 060-31-30W | 192 | 11/07/82 | 20/10/82 | WR | 50-80 % | S |
| 017 | PELICAN (LEIF M-48) | 2100 | 54-17-46N | 055-07-20W | 165 | 31/07/73 | 29/08/73 | WR | 50-80 % | S |
| 017 | PELICAN (BJARNI H-81) | 2100 | 55-30-00N | 057-42-00W | 139 | 31/08/73 | 25/10/73 | WR | 50-80 % | S |
| 017 | PELICAN (GUDRID H-55) | 2100 | 54-54-00N | 055-52-00W | 300 | 19/08/74 | 01/09/74 | WR | 50-80 % | S |
| 017 | PELICAN (BJARNI H-81) | 2100 | 55-30-44N | 057-45-00W | 139 | 30/09/74 | 17/10/74 | WR | 50-80 % | S |
| 017 | PELICAN (FREYDIS B-87) | 2100 | 53-56-13N | 054-42-35W | 188 | 05/07/75 | 05/08/75 | WR | 50-80 % | S |
| 017 | PELICAN (KARLSEFNI A-13) | 2100 | 58-52-00N | 061-46-00W | 180 | 11/08/75 | 23/09/75 | WR | 50-80 % | S |
| 017 | PELICAN (CARTIER D-70) | 2100 | 54-39-00N | 055-40-00W | 310 | 27/09/75 | 29/10/75 | WR | 50-80 % | S |
| 017 | PELICAN (SNORRI J-90) | 2100 | 57-20-00N | 059-58-00W | 141 | 29/08/76 | 07/09/76 | WR | 50-80 % | S |
| 017 | PELICAN (KARLSEFNI A-13) | 2100 | 58-52-00N | 061-47-00W | 180 | 13/09/76 | 23/10/76 | WR | 50-80 % | S |
| 017 | PELICAN (TYRK P-100) | 2100 | 55-30-00N | 058-14-00W | 137 | 27/07/79 | 25/08/79 | WR | 80-100% | S |
| 017 | PELICAN (GILBERT F-53) | 2100 | 58-52-06N | 062-06-20W | 183 | 14/09/79 | 08/10/79 | WR | 50-80 % | S |
| 017 | PELICAN (GILBERT F-53) | 2100 | 58-52-06N | 062-06-20W | 198 | 18/07/80 | 11/09/80 | WR | 50-80 % | S |

REFERENCE C81043D01

TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE        ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 023 | PETREL (CABOT G-91) | 2100 | 59-50-00N | 061-45-00W | 91 | 01/08/76 | 28/08/76 | WR | 80-100% | S |
| 023 | PETREL (VERRAZANO L-77) | 2100 | 52-26-05N | 054-12-00W | 107 | 03/09/76 | 22/09/76 | WR | 50-80 % | S |
| 023 | PETREL (BJARNI O-82) | 2100 | 55-31-47N | 057-42-34W | 144 | 30/07/79 | 20/10/79 | WR | 50-80 % | S |
| 023 | PETREL (RALEGH N-18) | 2200 | 62-17-53N | 062-32-51W | 357 | 13/09/82 | 02/10/82 | WR | 50-80 % | S |
| 122 | POINT GREY | 2900 | 49-17-03N | 123-16-22W | 11 | 05/07/78 | 12/08/78 | WR | 50-80 % | S |
| 122 | POINT GREY | 2900 | 49-16-42N | 123-16-00W | 5 | 22/08/78 | 30/07/79 | WR | 80-100% | S |
| 029 | POINT LEPREAU | 1860 | 44-57-00N | 066-27-00W | 91 | 21/05/75 | 01/06/76 | WR | 80-100% | S |
| 076 | POINT PELEE EAST | 2950 | 41-57-00N | 082-24-00W | 16 | 10/05/74 | 11/12/74 | WR | 50-80 % | S |
| 066 | POINT PELEE SOUTH | 2950 | 41-55-16N | 082-15-24W | 18 | 03/04/72 | 30/06/72 | WR | 80-100% | S |
| 066 | POINT PELEE SOUTH | 2950 | 41-55-16N | 082-15-24W | 18 | 02/09/72 | 13/11/72 | WR | 0-50 % | S |
| 066 | POINT PELEE SOUTH | 2950 | 41-55-16N | 082-15-24W | 18 | 31/03/73 | 29/12/73 | WR | 80-100% | S |
| 075 | POINT PELEE WEST | 2950 | 41-57-00N | 082-35-00W | 12 | 22/05/74 | 06/01/75 | WR | 80-100% | S |
| 152 | POINTE SAPIN | 2000 | 46-59-42N | 064-41-00W | 20 | 05/06/79 | 04/12/79 | WR | 80-100% | S |
| 152 | POINTE SAPIN | 2000 | 46-59-42N | 064-41-00W | 20 | 07/05/80 | 12/08/80 | WR | 50-80 % | S |
| 152 | POINTE SAPIN | 2000 | 46-59-42N | 064-39-00W | 20 | 14/08/82 | 18/11/82 | WR | 80-100% | S |
| 008 | PORT AUX BASQUES | 2000 | 47-33-00N | 059-06-00W | 44 | 05/12/74 | 07/02/75 | WR | 80-100% | S |
| 174 | PORT ELGIN (K) | 2950 | 44-26-45N | 081-24-50W | 2 | 18/05/77 | 27/11/77 | ST | 50-80 % | S |
| 175 | PORT ELGIN (WB) | 2950 | 44-27-00N | 081-25-00W | 11 | 18/05/77 | 29/11/77 | WR | 50-80 % | S |
| 182 | PORT HOPE | 2950 | 43-53-59N | 078-17-30W | 30 | 08/05/82 | 17/11/82 | WR | 0-50 % | S |
| 126 | PORT SIMPSON | 2900 | 54-35-18N | 130-25-34W | 37 | 01/05/81 | 02/03/82 | WR | 80-100% | S |
| 111 | POWELL RIVER (INNER) | 2900 | 49-50-18N | 124-31-50W | 6 | 10/12/76 | 14/03/77 | WR | 50-80 % | S |
| 112 | POWELL RIVER (OUTER) | 2900 | 49-50-18N | 124-31-50W | 9 | 10/12/76 | 14/03/77 | WR | 50-80 % | S |
| 104 | PRINCE RUPERT | 2900 | 54-11-09N | 130-30-06W | 91 | 28/09/72 | 13/06/73 | WR | 80-100% | S |
| 088 | PRINCE RUPERT | 2900 | 54-14-12N | 130-20-17W | 27 | 19/04/76 | 23/07/76 | WR | 50-80 % | S |
| 025 | PULLEN ISLAND | 2800 | 69-58-05N | 134-59-00W | 15 | 08/08/76 | 09/10/76 | WR | 80-100% | S |
| 050 | PULLEN ISLAND | 2800 | 69-57-05N | 133-50-05W | 15 | 08/08/76 | 08/10/76 | WR | 80-100% | S |
| 100 | QUADRA/VANCOUVER (OWS PAPA) | 3600 | 50-00-00N | 145-00-00W | 4000 | 02/02/74 | 11/02/74 | PC | 0-50 % | S |
| 100 | QUADRA/VANCOUVER (OWS PAPA) | 3600 | 50-00-00N | 145-00-00W | 4000 | 13/01/75 | 12/09/76 | PC | 80-100% | S |
| 100 | QUADRA/VANCOUVER (OWS PAPA) | 3600 | 50-00-00N | 145-00-00W | 4000 | 01/11/76 | 12/05/81 | PC | 80-100% | S |
| 001 | QUADRA/VANCOUVER (OWS PAPA (WB)) | 3600 | 50-00-00N | 145-00-00W | 4000 | 31/01/74 | 11/02/74 | WR | 50-80 % | S |
| 001 | QUADRA/VANCOUVER (OWS PAPA (WB)) | 3600 | 50-00-00N | 145-00-00W | 4000 | 04/04/75 | 08/05/75 | WR | 0-50 % | S |
| 001 | QUADRA/VANCOUVER (OWS PAPA (WB)) | 3600 | 50-00-00N | 145-00-00W | 4000 | 24/10/78 | 03/12/78 | WR | 80-100% | S |
| 001 | QUADRA/VANCOUVER (OWS PAPA (WB)) | 3600 | 50-00-00N | 145-00-00W | 4000 | 07/11/80 | 18/11/80 | WR | 80-100% | S |
| 053 | RIMOUSKI | 2000 | 48-31-15N | 068-28-25W | 7 | 13/08/71 | 24/11/71 | ST | 80-100% | S |
| 108 | ROBERTS BANK | 2900 | 49-01-05N | 123-16-07W | 139 | 07/02/74 | 01/11/74 | WR | 0-50 % | S |
| 108 | ROBERTS BANK | 2900 | 49-01-05N | 123-16-07W | 139 | 23/04/75 | 03/04/76 | WR | 50-80 % | S |
| 108 | ROBERTS BANK | 2900 | 49-04-18N | 123-22-48W | 250 | 25/06/81 | 29/06/81 | WR | 50-80 % | S |
| 151 | ROLLS COVE | 1800 | 47-34-00N | 052-41-10W | 18 | 20/09/80 | 18/09/81 | WR | 50-80 % | S |
| 142 | ROWAN JUNEAU (VENTURE B-13) | 1860 | 44-01-44N | 059-32-08W | 24 | 22/08/80 | 25/01/81 | WR | 80-100% | S |
| 142 | ROWAN JUNEAU (VENTURE B-43) | 1860 | 43-51-36N | 059-27-24W | 56 | 31/01/81 | 24/10/81 | WR | 80-100% | S |
| 142 | ROWAN JUNEAU (VENTURE B-43) | 1860 | 43-53-00N | 059-29-42W | 50 | 25/10/81 | 28/04/82 | WR | 80-100% | S |
| 142 | ROWAN JUNEAU (SOUTH VENTURE O-59) | 1860 | 43-52-36N | 059-29-12W | 50 | 29/04/82 | 03/01/83 | WR | 50-80 % | S |
| 153 | SALENERGY IV (EAST POINT E-47) | 2000 | 46-36-15N | 061-37-30W | 64 | 12/06/80 | 29/07/80 | WR | 50-80 % | S |
| 153 | SALENERGY IV (BEATON POINT F-70) | 2000 | 46-39-20N | 061-54-45W | 56 | 01/08/80 | 26/08/80 | WR | 80-100% | S |
| 143 | SAULNIERVILLE | 1860 | 44-15-20N | 066-[illegible]-00W | 9 | 27/05/77 | 03/06/77 | WR | 50-80 % | S |

## D. HISTORICAL WAVE MEASURING STATIONS

REFERENCE C81043D01



TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE    ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 143 | SAULNIERVILLE | 1860 | 44-15-50N | 066-08-45W | 7 | 03/06/77 | 11/11/77 | WR | 50-80 % | S |
| 143 | SAULNIERVILLE | 1860 | 44-15-20N | 066-10-00W | 9 | 12/11/77 | 22/03/79 | WR | 80-100% | S |
| 091 | SEDCO H (CAP ROUGE F-52) | 2000 | 47-11-10N | 061-11-10W | 61 | 13/06/73 | 03/09/73 | WR | 50-80 % | S |
| 091 | SEDCO H (BRADELLE L-49) | 2000 | 47-58-33N | 063-07-06W | 58 | 12/09/73 | 22/11/73 | WR | 50-80 % | S |
| 091 | SEDCO H (EMERILLON C-56) | 1851 | 45-15-03N | 054-23-14W | 120 | 06/12/73 | 22/01/74 | WR | 50-80 % | S |
| 091 | SEDCO H (OJIBWA E-07) | 1860 | 43-46-15N | 061-46-13W | 79 | 04/02/74 | 27/02/74 | WR | 50-80 % | S |
| 091 | SEDCO H (DEMASCOTA G-32) | 1860 | 43-41-25N | 060-49-51W | 53 | 04/03/74 | 19/05/74 | WR | 50-80 % | S |
| 091 | SEDCO H (SAMBRO I-29) | 1860 | 43-38-17N | 062-48-15W | 199 | 27/05/74 | 27/06/74 | WR | 50-80 % | S |
| 091 | SEDCO H (JASON C-20) | 1860 | 45-29-19N | 058-32-18W | 110 | 04/07/74 | 30/07/74 | WR | 50-80 % | S |
| 091 | SEDCO H (NORTH SYDNEY P-05) | 1860 | 46-34-45N | 059-45-00W | 100 | 16/08/74 | 03/09/74 | WR | 50-80 % | S |
| 091 | SEDCO H (MONTAGNAIS I-94) | 1860 | 42-53-41N | 064-13-47W | 113 | 15/09/74 | 28/09/74 | WR | 50-80 % | S |
| 091 | SEDCO H (NORTH SYDNEY F-24) | 1860 | 46-33-23N | 059-48-46W | 60 | 16/06/76 | 10/07/76 | WR | 50-80 % | S |
| 091 | SEDCO H (PENOBSCOT L-30) | 1860 | 44-09-44N | 060-04-09W | 138 | 26/07/76 | 22/09/76 | WR | 80-100% | S |
| 091 | SEDCO H (WENONAH J-75) | 1860 | 43-34-26N | 060-25-45W | 67 | 01/10/76 | 15/11/76 | WR | 0-50 % | S |
| 091 | SEDCO H (MOHEIDA P-15) | 1860 | 43-04-55N | 062-16-43W | 110 | 14/01/77 | 11/02/77 | WR | 50-80 % | S |
| 091 | SEDCO H (PENOBSCOT B-41) | 1860 | 44-10-02N | 060-06-32W | 61 | 24/02/77 | 29/03/77 | WR | 50-80 % | S |
| 093 | SEDCO I (EGRET K-36) | 1851 | 46-25-38N | 048-50-22W | 86 | 16/08/73 | 10/09/73 | WR | 80-100% | S |
| 093 | SEDCO I (SPOONBILL D-30) | 1851 | 45-49-06N | 049-04-06W | 64 | 13/09/73 | 14/10/73 | WR | 80-100% | S |
| 093 | SEDCO I (BRANT P-87) | 1851 | 44-16-59N | 052-42-19W | 86 | 02/12/73 | 10/12/73 | WR | 50-80 % | S |
| 093 | SEDCO I (COOT K-56) | 1851 | 45-45-41N | 052-08-32W | 86 | 20/02/74 | 21/02/74 | WR | 50-80 % | S |
| 093 | SEDCO I (CAREY J-34) | 1851 | 45-23-32N | 052-35-02W | 86 | 28/04/74 | 04/07/74 | WR | 0-50 % | S |
| 093 | SEDCO I (SKUA E-41) | 1851 | 45-20-27N | 048-52-26W | 85 | 10/09/74 | 29/09/74 | WR | 50-80 % | S |
| 090 | SEDCO J (FLYING FOAM I-13) | 1850 | 47-02-42N | 048-46-31W | 91 | 12/10/73 | 26/11/73 | WR | 50-80 % | S |
| 090 | SEDCO J (BONNITION H-32) | 1851 | 45-51-27N | 048-19-32W | 108 | 08/12/73 | 30/12/73 | WR | 50-80 % | S |
| 090 | SEDCO J (CITNALTA I-59) | 1860 | 44-08-42N | 059-37-30W | 59 | 25/02/74 | 19/04/74 | WR | 50-80 % | S |
| 090 | SEDCO J (INTREPID L-80) | 1860 | 43-49-37N | 059-56-44W | 37 | 14/06/74 | 11/08/74 | WR | 50-80 % | S |
| 090 | SEDCO J (ADOLPHUS D-50) | 1851 | 46-59-05N | 048-22-29W | 113 | 26/10/74 | 31/10/74 | WR | 50-80 % | S |
| 090 | SEDCO J (ADVENTURE F-80) | 1860 | 45-19-30N | 057-56-30W | 99 | 22/01/75 | 01/02/75 | WR | 50-80 % | S |
| 090 | SEDCO J (CUMBERLAND B-55) | 1800 | 48-24-12N | 050-07-58W | 195 | 08/08/75 | 13/10/75 | WR | 50-80 % | S |
| 090 | SEDCO J (INDIAN HARBOR M-52) | 2100 | 54-22-00N | 054-24-00W | 198 | 27/09/76 | 12/10/76 | WR | 50-80 % | S |
| 018 | SEDCO 445 (SNORRI J-90) | 2100 | 57-19-45N | 059-57-44W | 141 | 01/08/75 | 09/10/75 | WR | 50-80 % | S |
| 134 | SEDCO 706 (HIBERNIA B-08) | 1851 | 46-47-05N | 048-45-26W | 110 | 22/03/80 | 06/01/81 | WR | 50-80 % | S |
| 134 | SEDCO 706 (HEBRON I-13) | 1851 | 46-32-48N | 048-32-23W | 94 | 29/01/81 | 25/05/81 | WR | 80-100% | S |
| 134 | SEDCO 706 (HEBRON I-13) | 1851 | 46-32-20N | 048-31-35W | 70 | 22/07/81 | 10/09/81 | WR | 50-80 % | S |
| 134 | SEDCO 706 (NAUTILUS C-92) | 1800 | 46-51-21N | 048-44-55W | 90 | 22/10/81 | 14/07/82 | WR | 80-100% | S |
| 134 | SEDCO 706 (LINNET E-63) | 1800 | 48-12-48N | 050-25-50W | 157 | 23/07/82 | 06/11/82 | WR | 80-100% | S |
| 132 | SEDCO 707 (HARE BAY E-21) | 2100 | 51-10-23N | 051-04-30W | 241 | 12/06/79 | 18/10/79 | WR | 50-80 % | S |
| 133 | SEDCO 709 (HIBERNIA O-35) | 1851 | 46-44-21N | 048-49-00W | 72 | 07/01/80 | 11/07/80 | WR | 80-100% | S |
| 133 | SEDCO 709 (SHUBENACADIE H-100) | 1800 | 42-53-18N | 061-30-48W | 1114 | 19/11/82 | 23/12/82 | WR | 80-100% | S |
| 092 | SEDNETH (OSPREY H-84) | 1851 | 44-43-29N | 049-27-33W | 59 | 27/07/73 | 30/08/73 | WR | 80-100% | S |
| 051 | SEPT ILES | 2000 | 50-11-53N | 066-23-03W | 8 | 12/06/72 | 08/12/72 | PC | 80-100% | S |
| 161 | ST FABIEN | 2000 | 48-23-48N | 068-57-39W | 28 | 31/05/77 | 30/07/77 | WR | 80-100% | S |
| 052 | STE ANNE DES MONTS | 2000 | 49-09-15N | 066-30-00W | 61 | 07/07/71 | 29/11/71 | WR | 50-80 % | S |
| 052 | STE ANNE DES MONTS | 2000 | 49-09-15N | 066-30-00W | 61 | 09/06/72 | 22/11/72 | WR | 80-100% | S |
| 020 | STEPHENVILLE | 2000 | 48-29-24N | 058-42-00W | 28 | 07/10/74 | 29/10/74 | WR | 50-80 % | S |

FORM 17A(O)

CANADIAN MARINE DATA INVENTORY REPORT

D. HISTORICAL WAVE MEASURING STATIONS



REFERENCE C81043D01

TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE    ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 020 | STEPHENVILLE | 2000 | 48-29-24N | 058-42-00W | 28 | 06/12/74 | 19/01/75 | WR | 50-80 % | S |
| 020 | STEPHENVILLE | 2000 | 48-29-24N | 058-42-00W | 28 | 30/05/75 | 26/11/75 | WR | 50-80 % | S |
| 158 | STRAIT OF BELLE ISLE | 2000 | 51-22-27N | 056-49-55W | 101 | 12/06/81 | 28/10/81 | WR | 80-100% | S |
| 102 | STURGEON BANK | 2900 | 49-10-12N | 123-18-46W | 110 | 07/02/74 | 15/08/74 | WR | 80-100% | S |
| 102 | STURGEON BANK | 2900 | 49-10-12N | 123-18-46W | 110 | 18/11/74 | 01/04/76 | WR | 80-100% | S |
| 204 | TARSUIT ISLAND | 2800 | 69-53-00N | 136-11-00W | 20 | 13/08/81 | 15/08/81 | WR | 50-80 % | S |
| 204 | TARSUIT ISLAND | 2800 | 69-53-24N | 135-59-30W | 20 | 30/07/82 | 20/08/82 | WR | 80-100% | S |
| 204 | TARSUIT ISLAND (KIGGAVIK) | 2800 | 69-50-42N | 136-00-00W | 21 | 01/09/82 | 29/09/82 | WR | 50-80 % | S |
| 040 | TINER POINT | 1900 | 45-08-54N | 066-11-42W | 31 | 14/02/72 | 22/09/72 | WR | 80-100% | S |
| 040 | TINER POINT | 1900 | 45-09-15N | 066-10-46W | 31 | 24/09/72 | 22/03/73 | WR | 50-80 % | S |
| 040 | TINER POINT | 1900 | 45-08-33N | 066-12-23W | 14 | 26/01/77 | 22/05/78 | WR | 50-80 % | S |
| 056 | TINER POINT | 2000 | 45-09-12N | 066-12-12W | 8 | 21/04/77 | 12/06/78 | ST | 50-80 % | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 26/06/70 | 27/09/70 | WR | 0-50 % | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 02/04/71 | 21/05/71 | WR | 80-100% | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 07/07/71 | 20/12/71 | WR | 80-100% | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 02/02/72 | 12/07/72 | WR | 0-50 % | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 02/02/73 | 23/06/73 | WR | 80-100% | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 02/09/73 | 31/12/80 | WR | 80-100% | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 01/01/81 | 31/12/81 | WR | 50-80 % | S |
| 103 | TOFINO | 2900 | 48-59-27N | 125-44-39W | 40 | 01/01/82 | 31/12/82 | WR | 50-80 % | S |
| 065 | TORONTO | 2950 | 43-30-23N | 079-19-42W | 108 | 11/03/72 | 15/04/73 | WR | 80-100% | S |
| 003 | TUKTOYAKTUK | 2800 | 69-53-48N | 135-57-12W | 21 | 26/08/74 | 30/08/74 | WR | 80-100% | S |
| 003 | TUKTOYAKTUK | 2800 | 69-53-48N | 135-57-12W | 21 | 08/08/75 | 06/09/75 | WR | 80-100% | S |
| 004 | VICTORIA HARBOUR | 3600 | 48-25-25N | 123-23-16W | 5 | 10/03/76 | 24/03/77 | WR | 50-80 % | S |
| 095 | VICTORIA (K) | 2900 | 48-25-41N | 123-23-27W | 4 | 03/12/75 | 12/04/76 | ST | 50-80 % | S |
| 095 | VICTORIA (K) | 2900 | 48-25-41N | 123-23-27W | 4 | 09/07/76 | 28/07/76 | ST | 80-100% | S |
| 167 | VINLAND (WEST ESPERANTO B-78) | 1860 | 44-47-12N | 058-25-24W | 92 | 21/09/82 | 24/12/82 | WR | 50-80 % | S |
| 167 | VINLAND (WEST ESPERANTO B-78) | 1860 | 44-47-03N | 058-26-11W | 100 | 16/01/83 | 01/05/83 | WR | 50-80 % | S |
| 106 | WEST VANCOUVER | 2900 | 49-20-44N | 123-13-45W | 40 | 19/12/72 | 18/05/74 | WR | 50-80 % | S |
| 031 | WESTERN HEAD | 1860 | 44-00-42N | 064-36-12W | 40 | 27/04/70 | 04/07/71 | WR | 80-100% | S |
| 031 | WESTERN HEAD | 1860 | 44-00-49N | 064-36-10W | 43 | 03/09/71 | 04/05/72 | WR | 50-80 % | S |
| 031 | WESTERN HEAD | 1860 | 44-00-49N | 064-36-10W | 43 | 18/08/72 | 05/05/73 | WR | 50-80 % | S |
| 081 | WHEATLEY (K) | 2950 | 42-03-39N | 082-27-47W | 6 | 15/04/79 | 04/01/80 | ST | 50-80 % | S |
| 081 | WHEATLEY (K) | 2950 | 42-03-39N | 082-27-47W | 6 | 18/04/80 | 19/12/80 | ST | 50-80 % | S |
| 079 | WHEATLEY (WB) | 2950 | 42-02-00N | 082-27-00W | 13 | 11/04/79 | 26/12/79 | WR | 50-80 % | S |
| 079 | WHEATLEY (WB) | 2950 | 42-02-00N | 082-27-00W | 13 | 17/04/80 | 17/12/80 | WR | 50-80 % | S |
| 116 | WHITE ROCK | 2900 | 49-00-30N | 122-50-00W | 13 | 24/10/77 | 03/03/78 | WR | 80-100% | S |
| 165 | ZAPATA SCOTIAN (OLYMPIA A-12) | 1800 | 44-04-30N | 059-48-30W | 55 | 27/04/82 | 18/08/82 | WR | 80-100% | S |
| 165 | ZAPATA SCOTIAN (OLYMPIA A-12) | 1800 | 44-04-30N | 059-48-00W | 55 | 24/08/82 | 13/10/82 | WR | 50-80 % | S |
| 165 | ZAPATA SCOTIAN (OLYMPIA A-12) | 1800 | 44-00-43N | 059-47-18W | 37 | 15/10/82 | 23/10/82 | WR | 50-80 % | S |
| 165 | ZAPATA SCOTIAN (OLYMPIA A-12) | 1800 | 44-00-30N | 059-47-18W | 37 | 03/11/82 | 10/01/83 | WR | 50-80 % | S |
| 024 | ZAPATA UGLAND (HERJOLF M-92) | 2100 | 55-31-00N | 057-45-00W | 73 | 30/08/76 | 20/11/76 | WR | 50-80 % | S |
| 140 | ZAPATA UGLAND (HIBERNIA P-15) | 1851 | 46-46-20N | 048-46-00W | 82 | 25/11/79 | 07/01/80 | WR | 0-50 % | S |
| 140 | ZAPATA UGLAND (BEN NEVIS I-45) | 1851 | 46-34-36N | 048-21-15W | 98 | 31/01/80 | 30/08/80 | WR | 50-80 % | S |
| 140 | ZAPATA UGLAND (SOUTH TEMPEST G-88) | 1800 | 47-07-55N | 047-58-12W | 150 | 30/09/80 | 02/04/81 | WR | 50-80 % | S |

CANADIAN MARINE DATA INVENTORY REPORT

D. HISTORICAL WAVE MEASURING STATIONS



REFERENCE C81043D01

TYPE : WR - WAVERIDER, PC - PRESSURE CELL, ST - STAFF GAUGE        ANALYSIS : S - SPECTRAL

| IDENTIFICATION | | LOCATION | | | | DATES | | INSTRUMENT | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID. | NAME | IHB ZONE | LATITUDE DD-MM-SS | LONGITUDE DDD-MM-SS | DEPTH METRES | START DD/MM/YY | STOP DD/MM/YY | TYPE | SUCCESS-% | ANALYSIS |
| 140 | ZAPATA UGLAND (HIBERNIA K-18) | 1851 | 46-48-23N | 048-47-35W | 70 | 26/06/81 | 03/11/81 | WR | 50-80 % | S |
| 140 | ZAPATA UGLAND (WEST FLYING FOAM L-23) | 1800 | 47-03-12N | 048-44-48W | 95 | 15/11/81 | 19/02/82 | WR | 50-80 % | S |
| 140 | ZAPATA UGLAND (BONANZA M-71) | 1800 | 47-30-47N | 048-12-40W | 195 | 20/05/82 | 16/09/82 | WR | 50-80 % | S |
| 140 | ZAPATA UGLAND (BONANZA M-71) | 1800 | 47-30-40N | 048-12-23W | 201 | 16/10/82 | 11/12/82 | WR | 0-50 % | S |